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DICHROIC FILTER SPECIFICATION FOR COLOR ADDITIVE DISPLAYS:

II. Further Exploration of Tolerance Areas and the Influence of Other Display Variables

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FOREWORD

The effort described herein is part of a Rome Air Development Center in-house project. It is the final report in a series on the selection of dichroic filters to be employed in additive color film projection displays. The studies were initiated with Independent Research Funds (Discretionary Fund Item DS-63-15) and were continued as part of the regular in-house program of research under Project 5597, Task 559705. The author wishes to express his gratitude to the many members of the Display Techniques Branch who provided technical assistance. Special thanks are due Dr. R. J. Christman whose assistance made this report possible.

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ABSTRACT

Specification of primaries for seven-color display generation was examined under a wide range of conditions, including modifications to the equipment, manipulation of environmental variables, and control of response variables. The basic purpose of this series of studies was to increase the precision of previously determined specifications for dichroic filters to be employed in additive multicolored large-scale displays. The upper tolerance limit for the blue dichroic filter was determined to a high degree of precision. In addition, questions of filter order, character size, and brightness contrast were examined experimentally to determine their influence on filter specification.

As a summary contribution, an "ideal" seven-color additive system is outlined. Finally, recommendations are provided for situations wherein physical restrictions militate against the employment of the full seven color system approach.

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1. GENERAL INTRODUCTION

The first of a series of investigations undertaken at this facility on the use of dichroic filters for producing color coded displays (Rizy, 1965) examined the effects on display readability of three blue filters paired in every possible way with three red filters. Each group of filters included one filter used in the 465L (SACCS) system, a filter higher in cutoff point and a filter lower in cutoff point. It was concluded that blue filters as low as 498 nanometers (nm) at 50 percent cutoff (the filter used in the SACCS system) and red filters as high as 618 nm did not produce as satisfactory colors as the other filters. An optimum filter pair for high subject performance appeared to involve a blue filter with about a 516 nm cutoff and a red filter cutting off between 581 and 595 nm.

In order to more fully explore the identified cutoff areas, a second study (Rizy, 1966) was accomplished to verify the first findings and estimate tolerances in filter specification. The 581 and 595 red filters were compared as determinants of the red component; two other filters between 581 and 595 were used to explore any possible differences between the 581 and 595 filters; and three blue filters--516, 512 and 506 nm in cutoff--were paired with the red filters in an attempt to establish a lower limit on the blue filter cutoff. The lower limit for blue filters was determined when it was found that colors produced by the 506 filter were associated with significantly poorer subject performance than colors produced by the 512 or 516 blue filters. No <u>overall</u> significant differences were found among red filters. On a color-by-color basis, analysis pointed out that the 506 blue filter was poor for both the blue and red codes but was not significantly different from the other blue filters for the remaining color codes. The 581 red filter produced a better white than the 595 filter while, conversely, the 595 was related to a superior red, cyan and blue color code, in terms of subject performance.

Most of the observed effects were explainable in terms of filter cutoffs and were supported by comparison of obtained CIE chromaticity coordinates with previous findings in the area of color discrimination. Since the coding colors also differed in brightness and since the experimental task differed considerably from conventional psychophysical techniques, not all results were predictable, however. A theoretical framework for evaluating all multicolor coding systems on a color discriminability basis was discussed. In two subsequent in-house applications, this approach has appeared satisfactory.

Several questions remain to be answered: How high a cutoff may a blue filter have before color code degradation occurs? What are the upper and lower limits for red filter cutoff? What are the influences of other variables (<u>e.g.</u>, size of characters, order of dichroic filters in the optical assembly, contrast) on the specification and use of coding colors and dichroic filters?

The use of color has long been recognized as a valuable aid in increasing usefulness of the display (Conover & Kraft, 1958; Halsey, 1962; Jones, 1962). It is felt that the color-additive approach, employing dichroic

filters and relying on the registration of primaries to produce color codes, is far more simple and efficient than other approaches to the production of projected color and that readable, discriminable codes can be achieved without additional filtering. Hopefully, exploration of the remaining problem area associated with additive color will encourage wide usage of the technique until such time as possibly superior color generation techniques become available.

2. BLUE FILTER STUDIES

2.1. Introduction

Previous experimentation in the research task employed blue filters with cutoff points as high as 516 nm. There is nothing sacred about the 516 cutoff, and a higher cutoff might be a better recommendation provided it demonstrated significant improvement in the legibility of the blue color code without degrading other colors or inducing blue-cyan confusion. Therefore, it seemed quite important to explore above this level in order to determine the upper limit for tolerance specification.

Halsey (1963), in recommending filter parameters for an additive system, calculated that colorimetric requirements might best be met with two long wavelength reflectors: a red filter cutting off as low as 560 nm and a yellow filter of 535 nm cutoff. Essentially the same effect is obtainable when a blue filter of 535 nm cutoff is substituted for the yellow filter, except that, in the latter case, the blue color code, being reflected out first, would contain more energy than in the red-yellow arrangement where blue is the residual after red and green have been filtered out.

2.2. Latin-Square Experimental Design

2.2.1. Apparatus and Procedure

The viewing device was the Colorvision 70 mm Additive Color projector (see Rizy, 1965, for details), powered by a 2.2 kw xenon source. A 12 by 16 foot Trans-Lux white flat matte screen was positioned 39 feet from the projector lenses. The subject was seated slightly to the left of the projector, 40 feet from the screen center. Characters on the screen subtended a visual angle of 23 minutes of arc from the observer's position.

The projector optical system was aligned prior to experimentation. The lamp was driven at a 50 amp, 17-18 D.C. volt level, giving an open-gate brightness of seven foot-lamberts reflected from the screen, as measured by a Spectra spot photometer. A Hunter timer and solenoid shutter system limited exposure time for each trial to ten seconds. The display area was dark except for the desk lamps in the experimenter's and subject's locations. Ambient light was reflected from the screen on the order of .03 foot-lamberts.

Subjects were 10 males, nine college students and a young officer, with normal color vision, as measured by the color plate of the Bausch & Lomb

Orthorater, and with visual acuity for distance ranging from 20/18 to 20/29, corrected or uncorrected.

Subjects were given four practice trials for familiarization and then entered the experiment proper. A 7 x 10 completely-repeated measures design was used, with each subject responding to the seven coding colors produced by the ten filter pairs. Filters used were five blue filters, 512, 516, 521, 534 and 538 nm at 50 percent cutoff point, placed first in the optical assembly, and paired in each case with one of two red filters, 581 and 595 nm cutoff.

The ten filter pairs were presented to the ten subjects in a counter-balanced Latin square order, so that each subject viewed displays generated through the filter pairs in a different order. Five slides, each containing an alphanumeric matrix having all 36 characters appear in each of the seven colors in an 18 column by 14 row format, were used as stimuli. On the basis of previous experimentation, these slides were selected as being approximately equal in level of difficulty. The slides were presented twice to each subject in the experiment in serial order, so that each subject saw one alphanumeric slide on trials 1 and 6, another slide on trials 2 and 7, and so on. This procedure was established since it was found that, with modification to the projector, filter changing was easier than slide changing.

For the first trial, the first alphanumeric slide was inserted into the projector and the three primaries were focused and registered on the screen. The particular pair of filters scheduled for the first subject's first trial was installed. The first subject read as many of the alphanumerics of the designated color as he could within the 10-second exposure time. Seven readings were taken, one for each coding color. Then the filters were changed as required for the second subject. All ten subjects were tested before the slide was changed, thus keeping any anomaly in slide focus or registration the same throughout each trial. The number of correct responses per trial was recorded and analyzed as the final datum.

2.2.2. Results

Preliminary tests supported the hypothesis of homogeneity of variance within filter and color levels. The analysis of variance is summarized in Table 2.1.

The difference between coding colors identified in the analysis was consistent with previous findings. In practically zero ambient, performance on the red color code has been significantly better than that on other colors, and blue has resulted in generally higher performance, although not significantly, than green or cyan (Snadowsky, Rizy and Elias, 1964). Specific tests between means for the various color codes were calculated with the Tukey (a) method (Winer, 1962) and the results summarized in Table 2.2.

Table 2.1.

Summary of Analysis of Variance for Filters
Presented in Latin Square Order

Source of Variance	d.f.	Mean Squares	F-Ratio	Probability
Between Subjects	9			
Within Subjects	690			
Filter Pairs	9	6.93	1.02	non-signif.
Coding Colors	6	381.78	56.20	$< .01$
FB x CC	54	5.50	.81	non-signif.
Error	621	6.79		

Table 2.2.

Significance of Differences Between Means
for the Seven Coding Colors *,**

Red	Yellow	White	Magenta	Blue	Green	Cyan
15.50	13.34	12.59	12.32	11.01	10.29	9.85

*Scores reported in mean number correct responses per 10-second trial.

**Means connected by a line were not significantly different at the .05 level of confidence.

2.2.3. Discussion

No statistically supportable differences were found between filter pairs or in the interaction of filter pairs with coding colors. The differences found previously between the 512 and 516 blue filters and the 581 and 595 red filters---in interaction with coding colors---either did not occur or were in some way masked.

Differences among filters were also tested with a nonparametric analog of the analysis of variance, the Friedman test of ranks (Siegal, 1956), to determine whether possible failure to meet the additional assumption of the repeated measures design, i.e., homogenous covariance, might have contributed to the unexpected insignificant result. The resultant $\chi_r^2 = 6.13$ was distributed as Chi-square with 9 degrees of freedom and was not significant ($.8 > p > .7$).

Due to the nature of the experimental design, within-cell variance was a function of learning and of differences between slides, as well as random

error. It was conceivable that real differences between filters were small relative to the large error term. Also, since few data were taken, compared to past experiments, and since the subject viewed only one stimulus slide per filter pair---effectively preventing him from becoming accustomed to any set of filters, another possible source of variability---it appeared advisable to repeat the experimental conditions using a different experimental design.

2.3. Counterbalanced Partially-Repeated Measures Design

2.3.1. Apparatus and Procedure

The equipment and display parameters of the second study were the same as the first, i.e., apparent size of characters, minimal ambient, open-gate brightness, and exposure time. A 2 x 6 x 7 design (Winer's Case I of partially repeated measures, 1962) was followed. Each group of four subjects viewed displays produced by only one of the two red filters, 581 or 595 nm cutoff (the unrepeated factor). All eight subjects saw displays involving six blue filters, 506, 512, 516, 521, 534 and 538 nm, four in an ascending series of blue cutoff wavelengths (two viewing displays with the 581 red filter, two with the 595 red filter) and the other four in a descending series of presentations. All subjects read sequentially, in separate exposures, alphanumerics in the seven color codes.

Chromaticity coordinates of the primaries, obtained with an Instrument Development Laboratories' Color-Rad (abridged ratio-type colorimeter-spectroradiometer), Model D-1, appear in Figure 2.1. The blue primaries showed a regular rise in green component with increasing 50 percent cutoff wavelength, although the chromaticities of the red primaries were not appreciably affected. The green primaries evidenced residual effects of both blue and red filters. White is plotted separately for the 506 and 512 filters and for the 516 through 538 filters (see Rizy, 1966).

Subjects were eight male college students meeting the same criteria as those used in the first study. They were given six practice trials each on the standard 465L filter set, the 498 blue and 595 red filters, for familiarization with color codes and tasks.

For each blue-red filter arrangement, a subject was required to respond to six alphanumeric matrices, the same matrices each time and presented in the same order. The first two matrices were considered as a practice set, to allow familiarization with the particular set of coding colors. Only responses to the last four matrices were statistically analyzed, although subjects were not informed of this. The experimental task was the same as before. Given a color name, the subject was to read as many symbols of that color as he could when the display appeared on the screen.

2.3.2. Results

2.3.2.1. Preliminary Tests and Overall Analysis

The F_{max} test for homogeneity of variance was calculated using the counterbalanced scores (counterbalanced in order of blue filter presentation)

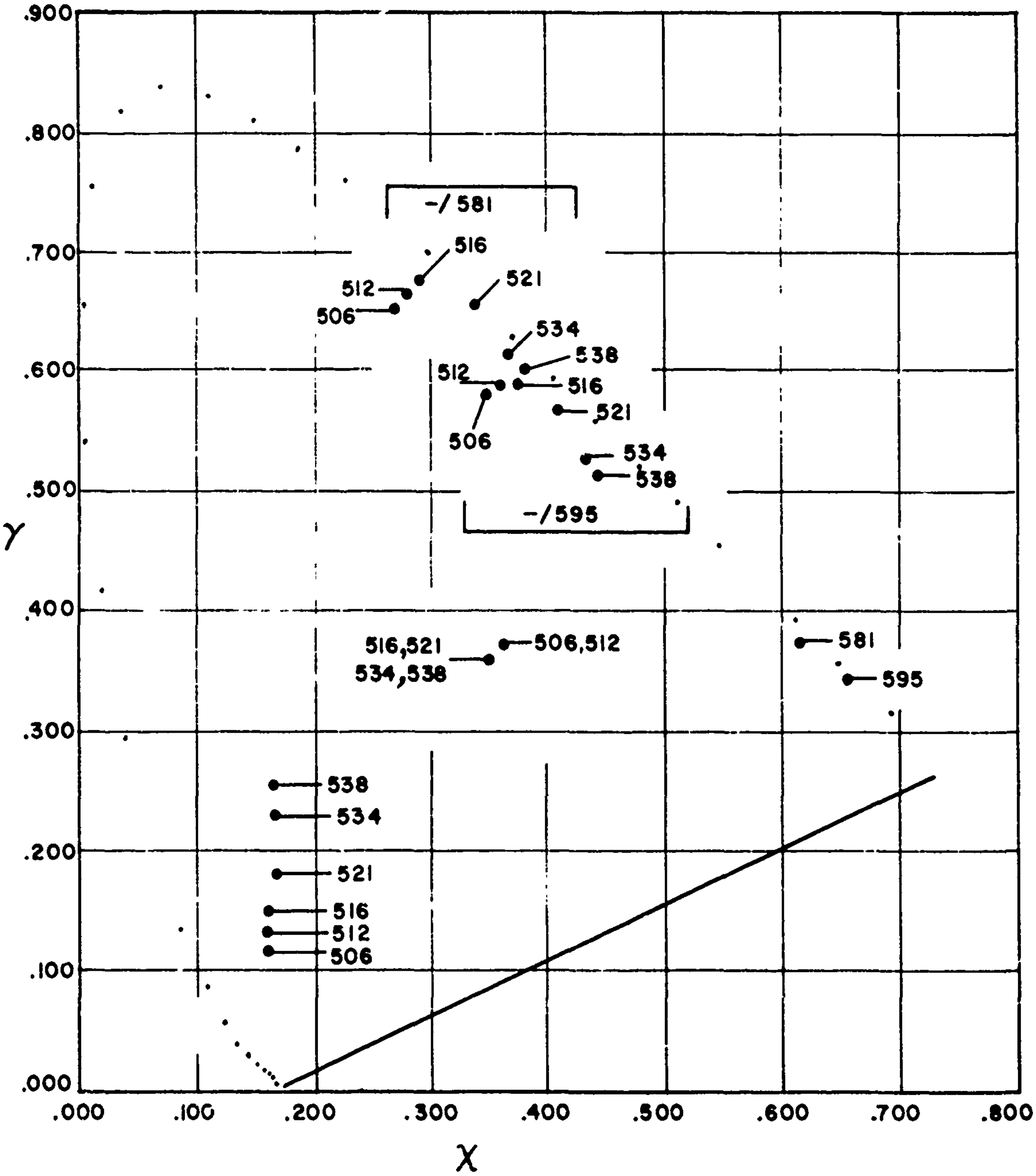

Fig 2.1 Chromaticity Coordinates of the Three Primaries and White
(All combinations of six blue and two red dichroics)

of the four subjects in each red filter group. A further differentiation into order-filter levels would have given only one degree of freedom in the denominator of the test, for which tabled values of the F_{max} distribution are not available and where, presumably, the power of the F_{max} test is not adequate. Henceforth, order was disregarded in the analyses.

The ratio between error variances for each of the two groups was not significant for Subjects within groups nor Colors by Subjects. The Blue Filters by Colors by Subjects term was of questionable homogeneity ($.05 > p > .01$). The tests were recalculated with data transformed to the square root, and all resultant F_{max} tests yielded nonsignificant results.

Homogeneity of the covariance matrices was tested with the method suggested by Box (Winer, 1962), employing comparisons of the determinants of the matrices of the two groups of subjects, a pooled matrix, and a special matrix containing an averaged variance on the diagonal, an averaged covariance off the diagonal. The hypothesis of homogeneity was supported for both original and transformed scores. The analysis of variance was calculated for both original and transformed data (see Table 2.3), and the results were essentially the same.

Table 2.3.

Summary of Analysis of Variance for Counterbalanced Design Using Both Original and Transformed ($Y = \sqrt{X}$) Scores

Source of Variation	d.f.	Original Scores Mean Square	F	Transformed Scores Mean Square	F
Between Subjects	7				
Red Filters (R)	1	19,186.08	1.53	77.8798	1.51
Subjects w. groups	6	12,540.50		51.7192	
Within Subjects	328				
Blue Filters (B)	5	224.24	1.25	.9993	1.28
RB	5	59.44	.33	.3423	.44
B x subj w. groups	30	178.88		.7793	
Colors (C)	6	2,473.38	14.66**	11.6644	12.69**
RC	6	471.02	2.79*	2.8620	3.11*
C x subj w. groups	36	168.74		.9193	
BC	30	44.29	4.48**	.2328	5.09**
RBC	30	9.68	.98	.0392	.86
BC x subj w. groups	180	9.88		.0458	

*$p < .05$
**$p < .01$

There was no significant difference between the two red filters averaged over all conditions nor were the blue filters as a group different in the overall F-test. A highly significant result was found comparing colors overall, and this was partially a function of which blue filter (BC effect) or which red filter (RC effect) was used. The overall interaction of Red Filter-blue Filter-Coding Color was not significant, indicating that the particular colored filter by coding color interactions were sufficient to account for deviations from the coding colors' overall effect on performance.

2.3.2.2. Tests of Main Effects

The overall color code differences were tested with the conservative Tukey (a) procedure (Winer, 1962), disregarding for the moment the color by filter interactions. The tests, summarized in Table 2.4., were relatively unplanned or "a posteriori" since no basis existed for predicting the relative efficiency of coding colors in negligible ambient except the Snadowsky study

Table 2.4.

A Posteriori Comparisons Between Overall Treatment Means for Coding Colors*,**

Red	Yellow	Magenta	White	Blue	Green	Cyan
69.21	60.56	56.35	56.19	54.58	50.23	47.10

*Scores reported in mean number correct responses for 10-second exposures to four slides.

**Means connected by a line are not significant at the .05 level of confidence.

on misregistration (1964). Also, the projector outputs of the two studies differed by an order of magnitude. Finally, the gross appearance of most of the colors was altered perceptibly with the installation of the high cutoff blue filters 534 and 538, making prediction of color code handling efficiency tenuous, even disregarding the effect of ambient level.

Results of the tests indicated marked similarity to the Snadowsky study's order of performance on coding colors at zero misregistration, except for the blue color code. In the Snadowsky investigation, the extreme high brightness of the display seemed to make blue a highly legible coding color.

Individual comparisons were calculated for overall differences between blue filters, to test the main hypothesis of the study. It was felt, on the basis of the findings given in the second report (Rizy, 1966), that the 512 and 516 filters should be considered as optimal and that a priori comparisons were justified. Results of the tests are summarized in Table 2.5. Only one difference was apparent in the data: the 512, 516 and 506 blue filters were significantly different from the 538 filter.

Table 2.5.

Summary of Individual Comparisons
Between Treatment Means for Blue Filters*,**

Blue Dichroic Filters in Terms of 50 Percent Cutoff					
512	516	506	534	521	538
58.20	58.18	57.61	55.48	55.20	53.25

*Scores reported in mean number of correct responses for 10-second exposures to four slides.

** Means connected by a line are not significant at the .05 confidence level.

Three possibilities may be cited for the lack of clear-cut results. There may be no difference in subject performance, despite the differences in appearance of colors; or not enough data were gathered in a situation where more variation was present than in past similar studies; or, finally, effects of filters on reading color-coded displays is minimal when ambient light is extremely low.

2.3.2.3. The Interaction of Filters and Colors

Tests of the simple effects of red filters across symbol colors by a t-test suggested by Cochran and Cox (Winer, 1962) yielded no specific significant differences, despite the occurrence of the significant Red Filter by Color Interaction. Even if significant differences were identified (as in Rizy, 1966), straightforward interpretation would be impractical since red filters were confounded with group effects.

The completely within subjects interaction of blue filters by colors was of far more interest and was an effect the experiment was specifically designed to test. The Tukey (a) test was used as a conservative approach to the determination of differences between subject performance on each of the seven color codes. Tests were calculated on transformed scores since homogeneity of variance for the BC x subjects interaction was questionable for untransformed data. The results are presented in Table 2.6.

Table 2.6.

A Posteriori Comparisons Between Mean Subject Performances Under Each of Six Blue Filter Conditions on Each Color Code*,**

Color Code	Blue Filters					
White, Red, Green, Blue	No significant differences					
Yellow	534	516	538	506	512	521
	63.12	61.37	60.75	60.37	59.87	57.87
Magenta	506	512	516	521	534	538
	61.50	60.50	59.00	57.25	51.88	48.00
Cyan	506	512	516	521	534	538
	51.50	50.37	49.75	46.00	44.87	40.12

* Scores reported as untransformed means, although tests were conducted on transformed data.

**Means connected by a line are not significantly different at the .05 level of confidence.

The Blue filter by Color Code interaction is also presented in Figure 2.2. It may be noted that white, red, green and blue color codes were not statistically affected by blue filters as far as subject performance was concerned, although the chromaticities of the blue and green, at least, were a function of the particular blue filter used (Figure 2.1.).

An anomalous result was observed in performance on the yellow code. The 534 blue filter was associated with higher subject performance than the 521 filter, although no further differences were apparent. There was no trend apparent in the relationship of scores and filters. This result may have occurred by chance and have been an instance of "type 1" error. Conceivably, it might also be due to some peculiarity in the 521 blue filter, although the 521, 534 and 538 were obtained from the same manufacturer. Finally, it is possible that a curvilinear relationship exists between performance on the yellow code and the blue filter cutoff. From prior observation, it seemed to the experimenter and other laboratory personnel that the 534 and 538 filters were associated with a dark yellow, bordering on a yellow-orange. The same effect was noted to a lesser extent with the 521 filter. Confusion between yellow and white appeared very unlikely and improvement in subject performance was anticipated. Since this improvement did not occur, it might be feasible to hypothesize at least two maxima in the relation: one in the

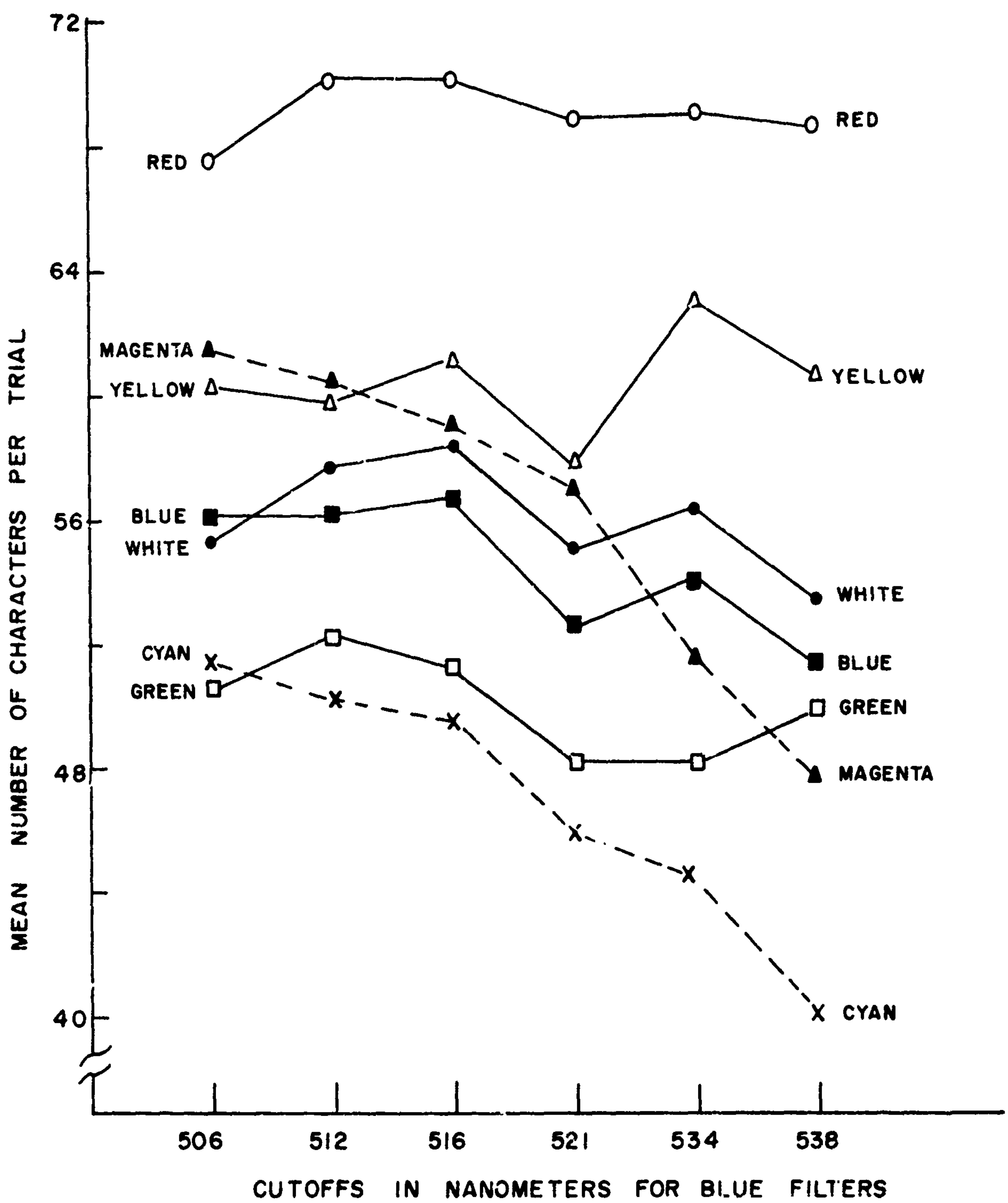

Fig 2.2 Subject Performance as a Function of Blue Filter Cutoffs and Color Codes

area of 516 nm, where colors were generally discriminable and, much below which, yellow approached the appearance of white because of the desaturation of the green component. At the other maximum, around 534 nm, yellow is considerably darkened, hence easily discriminable from white. Much above 534, yellow should continue to lose brightness and the green component until it finally becomes indistinguishable from red. Performance at 521 might then represent some kind of crossover point, where yellow is not bright enough to stand out on the display but not dim enough to be discriminated clearly from white.

Magenta was directly dependent upon the blue filter cutoff. As had been expected (Rizy, 1966), the higher the cutoff in blue, the less saturated the magenta; the less saturated the magenta, the poorer subject performance became because of the decrease in the chromatic uniqueness of the color and its ability, for lack of a better word, to "catch the eye." It may also be noted that poorer performance occurred despite increased brightness.

Performance on cyan was also related to the cutoff of the blue filter. At the high end of the blue filter range, subjects reported cyan-blue confusion. Explanation of the superiority of the low-end filter, 506, is difficult in terms of chromaticity, as this cyan is quite light in color and would seem to be confusable with either white or green. However, at the low end, the difference between cyan and green may have been accentuated, as the greens produced by the lower cutoff blue filters contained more wavelengths in the green region and appeared more true green than the greens produced by the high cutoff blue filters. These latter appeared yellow-green. It has previously been noted that yellow-greens seem more confusable with cyan than greens of equal saturation (Rizy, 1966).

2.3.3. Discussion and Conclusions

In environments where ambient lighting is negligible, the tolerance of filter specification does not seem to be as critical as where a moderate or high level of ambient lighting is present. The two studies reported here used a wide variety of blue filters, with cutoffs ranging from 506 to 538 nm. A previous study (Rizy, 1966) had found significant differences between the 506 and the 512 and 516 blue filters, but present experiments either were not as sensitive or, more likely, reflected the effect of ambient illumination on filter specification.

With regard to sensitivity, two quite different designs were used, one essentially the same as that employed in the earlier dichroic investigations, the partially repeated measures design; the other was a completely repeated measures Latin square randomization of subjects and filters. There was no evidence to justify the assertion that these latter designs were less sensitive, although this possibility cannot be completely ruled out. A comparison of the within group variation of the three partially repeated designs used in filter studies yielded a coefficient of variation, V, equal to 19.777 (Rizy, 1965), 7.279 (Rizy, 1966) and 7.953 (the second study presented here). The greatest amount of within cell variation was found in the first study, but the filters used had the most heterogenous cutoffs of the three studies.

There was little apparent difference between variability of the second and third studies, implying one dimension of sensitivity, random error, was comparable.

Another dimension of sensitivity was the number of observations per experimental unit, i.e., pair of filters. In the 1966 study, 336 measurements were made per filter pair; in the 1965 study, 504 observations; and in the present second study, 112. Perhaps on this basis, some case for loss of sensitivity might be made; but also, presumably, refinement of experimental technique in the course of the study program warranted some economies in investigation.

The assumptions underlying the partially repeated measures design were fully tested and, except in one case, supported. A transformation was used to correct for the lack of homogeneity in the BC times subjects interaction. The only alternative left to explain the lack of significant overall blue filter differences appeared to be the lack of ambient illumination.

This does not seem to be a far-fetched postulate. Ambient can drastically affect the legibility of coding colors, notably blue. It is likely that some residual effects of filters are present in minimal ambient conditions but are so small that they might require a more sensitive measure than is currently used, such as eye-movement recording, or might even show up as effects in long-term viewing and performance.

The data give some indication, however, that even in minimal ambient it is probably wisest to specify the blue filter in the 512-516 range. A modicum of statistical evidence indicated that, whereas no statistical improvement could be detected in any color code using high-cutoff filters, two coding colors were related to statistically lower performance using the higher cutoffs, magenta and cyan. Pending evaluation of the same filter sets at moderate and high ambient, it is still recommended that xenon-powered color additive projectors use blue dichroic filters with 50 percent cutoff in the 512-516 nm region.

3. EFFECT OF ORDER OF DICHROIC FILTERS UPON THE RELATIVE LEGIBILITY OF COLORED SYMBOLS

3.1. Introduction

Up to seven coding colors are available for coding purposes through the technique of two-dichroic color addition. The customary filter order, used in the 465L command and control system and in the Orthicon color television system, places the blue filter first in the optical pathway, to compensate for low luminosity in the blue field by giving it "first bite" into available light, followed by a red reflecting dichroic, with the residue passing through both filters and emerging as green.

Recent applications of color coding, e.g., 416L, 473L, have tended to avoid the use of blue as a coding color and relegated its use, if at all, to a background function. It is conceivable that other orders of filters, still producing the seven conventional codes, while being detrimental to blue might

enhance coding characteristics of other symbol colors and might therefore be of greater usefulness in systems which avoid the use of blue.

The investigation reported here was more of an exploratory nature than a formal investigation, and conclusions drawn were meant to be suggestive. The intent of the study was to open the possibility for further research.

3.2. Apparatus and Procedure

3.2.1. Equipment and Display Variables

The display equipment and timing system were as previously described. The data were obtained before the display system was moved to its present location, and consequently the environmental variables were those of the 1966 study. The display screen was a six-by-eight foot white Lux-Matte front projection screen, 24 feet, 4 inches from the projection lenses. Ambient level was .33 foot-lamberts reflected from the screen face to the viewing position, generated from a fluorescent desk lamp at the rear of the display area.

The current to the partly defocused xenon lamp was kept at a constant 68 amps, 19 D.C. volts, giving an open-gate brightness of 4.8 foot-lamberts reflected from the screen, as measured by the Spectra spot photometer. Exposure time for each slide on the screen was set at 12 seconds.

Misregistration was kept to a maximum of 33 percent of stroke width. Dichroic filters used were a blue filter cutting off at 516 nm and two red dichroics cutting off at 581 and 595 nm respectively. This gave two pairs of dichroic filters, 516-581 and 516-595, which were installed in the projector optical assembly in both the order of blue-red and red-blue, effectively producing four pairs of dichroic filters. Color-Rad measurements of the obtained primaries are plotted in Figure 3.1. The red-blue filter order can be observed reducing the saturation of red and having the reverse effect upon blue. No change was detected in green; hence no plot was made for the separate orders.

The two alphanumeric randomizations used were of the same dimension previously used, 14 rows by 18 columns, but the alphanumerics were grouped in triads, three symbols of the same color per group. Hence, the first slide used began, in the first row, with three red characters, then three white, three yellow, and so on. The order of colors on each slide and the alphanumeric content of each triad were randomized.

3.2.2. Subjects

The 12 subjects used in the experiment were college students with normal color vision and visual acuity, as defined by the criteria described in Part 2. They had just completed work in the study on blue and red filters (Rizy, 1966) and were considered to be well-trained. They sat 22.5 feet from the screen, where the displayed characters subtended a visual angle of 27 minutes of arc.

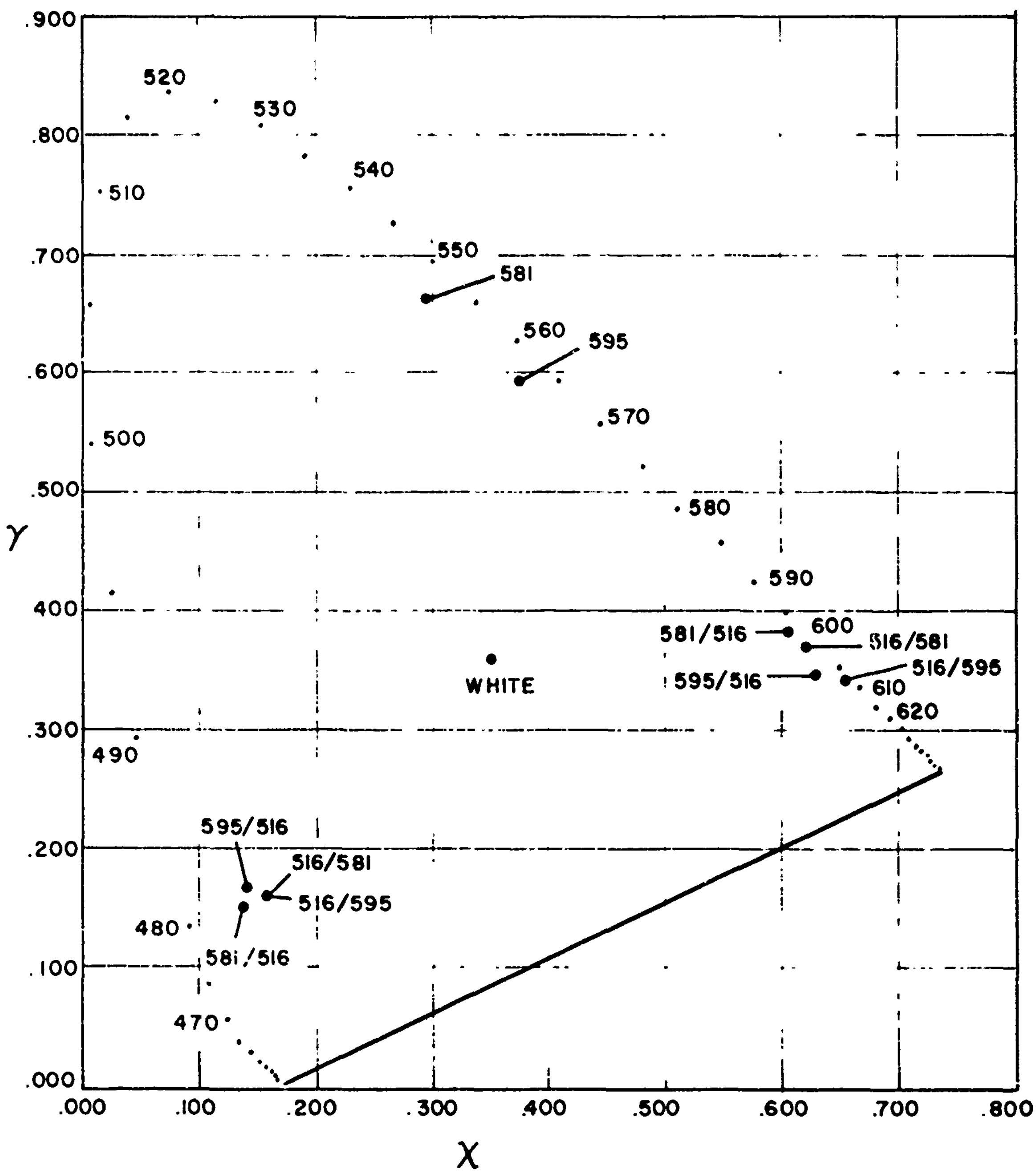

Fig 3.1 Chromaticity Coordinates for the Three Primaries Produced by Blue-red and Red-blue Dichroic Sequences

3.2.3. Experimental Design

A five-way partially repeated measures design was used. There were two orders of presentation used, counterbalanced across order of filters and alphanumeric slides in a Graeco-latin 2 x 2 x 2 square. Order was a non-repeated factor.

There were two pairs of filters used, the 516-581 and the 516-595, six subjects viewing displays produced through each pair in both filter orders, blue-red and red-blue. Three subjects in each group viewed blue-red first, and three viewed red-blue first.

There were three repeated measures included: all subjects responded to seven color codes on each trial; viewed both orders of filters, blue-red and red-blue; and saw the same two alphanumeric slides.

All subjects were instructed about the changes in the slide format from complete randomization of color to presentation in triad color groups. It was emphasized that the task was to be the same as in the previous experiment, i.e., to read as many alphanumerics of the color designated by the experimenter as possible within the time they are exposed on the screen. A stimulus slide was then briefly exposed to orient the subject toward the reorganized stimuli. Finally, the experiment was begun and data were collected according to the schedule outlined above.

3.3. Results

An analysis of variance for a 2^5 factorial design with the last three factors completely repeated was calculated and is summarized in Table 3.1. It may be noted that order of presentation showed significant differences, an effect completely confounded with group differences. Among other main effects, only color was significant. Order of filters had no overall significant effect upon performance, a result not completely unexpected. Among the significant interaction effects were Order of Filters by Slides and Colors by Order of Filters by Slides. One interaction which was expected to show significant differences but did not in the overall F-test, was the Colors by Filter Order effect. It had been hypothesized that changing the order of filters would change the relative readability of color codes.

Key effects were explored more fully with tests of specific differences. The main effect of colors was analyzed with a Tukey (a) test and indicated that, averaged over all other conditions, yellow, magenta, red, and white formed the high group of coding colors in terms of subject performance and were not significantly different from one another. Green and cyan led to intermediate subject performance, and reading blue symbols was significantly poorer than performance on the other color codes.

TABLE 3.1.

Summary of Analysis of Variance for Filter Order Effects

Source of Variation	d.f.	Mean Square	F-Ratio	Probability
Between Subjects	11			
O (Order of Presentation	1	3,490.74	9.62	.025
F (Filter Pairs)	1	747.03	2.06	n.s.
OF	1	342.03	.94	n.s.
Subjects within groups	8	362.92		
Within Subjects	324			
C (Coding Colors)	6	282.18	9.64	.01
OC	6	11.80	.40	n.s.
FC	6	14.15	.48	n.s.
OFC	6	5.25	.18	n.s.
C x subj w groups	48	29.28		
D (Order of Dichroics)	1	3.24	.45	n.s.
OD	1	7.15	1.00	n.s.
FD	1	.01	.01	n.s.
OFD	1	.24	.03	n.s.
D x subj w groups	8	7.15		
S (Slides)	1	10.36	1.06	n.s.
OS	1	1.07	.11	n.s.
FS	1	.24	.02	n.s.
OFS	1	15.00	1.54	n.s.
S x subj w groups	8	9.75		
CD	6	17.16	2.07	n.s.
OCD	6	1.74	.21	n.s.
FCD	6	5.42	.65	n.s.
OFCD	6	7.53	.91	n.s.
CD x subj w groups	48	8.30		
CS	6	15.21	1.68	n.s.
OCS	6	14.69	1.62	n.s.
FCS	6	10.17	1.12	n.s.
OFCS	6	2.23	.25	n.s.
CS x subj w groups	48	9.04		
DS	1	140.15	7.14	.05
ODS	1	1.86	.09	n.s.
FDS	1	1.31	.07	n.s.
OFDS	1	25.74	1.31	n.s.
DS x subj w groups	1	19.63		
CDS	6	20.90	3.36	.01
OCDS	6	13.76	2.21	n.s.
FCDS	6	3.73	.60	n.s.
OFCDS	6	11.84	1.90	n.s.
CDS x subj w groups	48	6.22		

The relative efficiency of colors in each of the two filter orders was also examined with the Tukey (a) test. For the blue-red filter order, colors were separated into two mutually exclusive groups, statistically: yellow, white, red, and magenta in the high group; green, cyan, and blue in the low group. Findings in the red-blue filter order were less clear-cut and are summarized in Table 3.2. where they may be compared with the blue-red order.

Table 3.2.

Summary of Tests Between Means of Subject Performance on Coding Colors for the Two Filter Orders*

1. Blue-Red Order	Yellow	White	Red	Magenta	Green	Cyan	Blue
	29.25	28.46	28.42	28.29	25.12	24.12	23.42
2. Red-Blue Order	Yellow	Magenta	Red	White	Cyan	Green	Blue
	30.00	28.50	28.33	27.54	26.46	25.54	22.08

*Means connected by a line were not significantly different at the .05 level of confidence

When the relative efficiencies of coding colors were tested from the opposite viewpoint, namely, comparing the simple effect of a coding color in each of the two filter orders, only one significant difference was found: performance in the cyan color code improved significantly with a probability of chance occurrence of the observed magnitude of the difference less than .05. These comparisons are shown in Figure 3.2., where another difference, between the two performances on blue, while of more than a unit magnitude, was not statistically significant.

Order of presentation (of filter orders and slides), an unrepeated factor confounded with differences between groups of subjects, showed a significant difference. Apparently, the group that viewed the red-blue filter order and the second slide first in the experiment had significantly higher scores than the other group. The most obvious explanation for the difference was chance assignment of high performers to the former group and low scoring subjects to the latter. Since order of presentation did not significantly interact with any other factor, it was felt that order could be safely ignored.

The significant interactions of Filter Order by Slides and of Colors by Filter Order by Slides indicated that, despite randomization, arrangements of symbols in a matrix, at least in triads, have their own particular difficulty level, independent of other factors. Some groups of symbols were easier to read, possibly easier to enunciate. Change of filter order put some symbols into another color code and left other symbols unchanged. In this case, changing from the conventional blue-red filter order to the red-blue caused symbols previously red to appear in blue and vice versa; yellow and cyan symbology interchanged; white, green, and magenta remained as before.

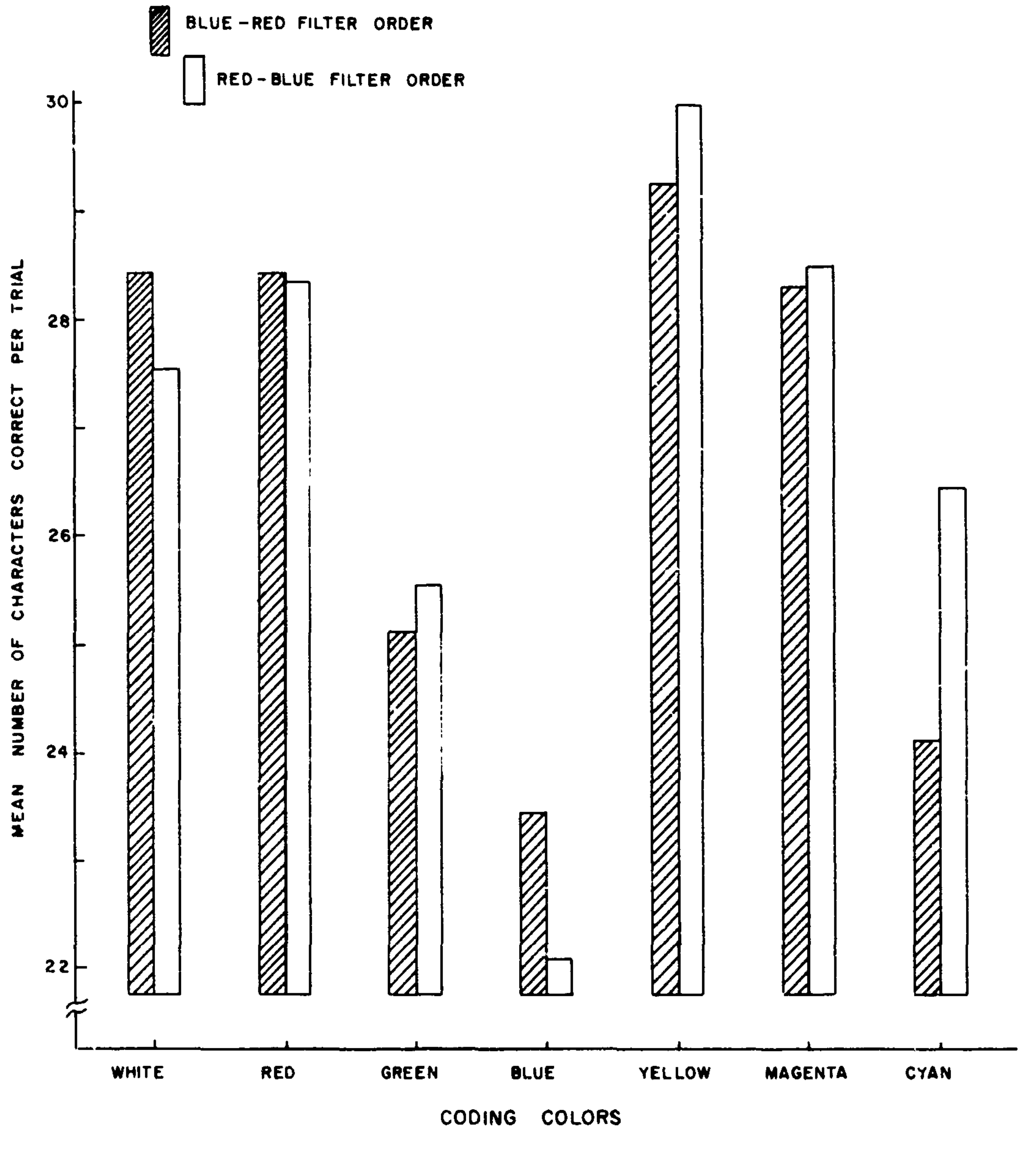

Fig 3.2 Subjects' Performance with the Blue-red and Red-blue Filter Orders

The overall effect of the orders of characters on the slides was that the specific effects cancelled out, making the overall difficulty level between slides statistically nonsignificant.

3.4. Discussion

It had at one time been supposed that the filter-order effects would be minimal (Rizy, 1966), but on the basis of evidence uncovered by this exploratory examination, it would seem safe to conclude that the particular order of filters used may have a decided effect upon certain colors, thus presenting the systems engineer with another technique for customizing the color codes to fit the user's needs.

There was statistical evidence to support the finding that the red-blue order produced a better cyan. Analysis of the first study's data (1965) had indicated green and cyan were highly confusable. It might be supposed that this filter order somehow accentuated the difference between these two coding colors.Several other possible instances of color codes shifting efficiency with changing filter order should be noted. These tendencies are mentioned on the premise that more extensive testing might indicate true significant differences between filter orders for the colors involved. Performance on the blue color code decreased and increased slightly for the green and yellow with the change to red-blue order.

When the blue filter is placed first in the system, it reflects into the blue channel energies in the blue and blue-green region plus about five percent of the energy in the rest of the spectrum. Hence, the blue conventionally used has been brighter and somewhat less saturated than if just wavelengths in the blue region were employed. When the order of filters is reversed, the red reflecting dichroic now reflects out practically all of the red wavelengths and approximately five percent of the rest of the spectrum, including some of the blue, before the light reaches the blue filter. As a result, the blue primary is more saturated but less bright. Whereas the blue by itself as a color code becomes less legible, it would seem to make for a more saturated cyan and consequently a cyan more discriminable from green. The net effect is very similar to using a blue dichroic with a cutoff nearer the ultraviolet. Magenta and white are unaffected, provided no substantial amount of light is deflected from the system at either the first or second dichroic position. Yellow would probably decrease in saturation and also shift toward red, since the red component in the red-blue filter order would increase in energy. This would seem to enhance the difference between yellow and white, thus leading to a prediction of improvement in test scores. In view of the results cited in section 2., however, the expected performance improvement might be minimal.

3.5. Conclusions

Definitive conclusions cannot be drawn in view of the lack of statistical significance for effects of major experimental interest. It is unlikely that any major alterations in display legibility may occur through changing the order of filters. However, <u>some</u> improvement in <u>certain</u> colors may be

achieved by this approach; i.e., where blue will not be used as a coding color, using a red-blue filter order apparently improves cyan. Further research seems warranted.

4. EFFECT OF CHARACTER SIZE ON THE LEGIBILITY OF CHARACTERS IN A SEVEN-COLOR DISPLAY

4.1. Introduction

One of the first questions that comes to mind when discussing visual displays is, "How big should the symbols be?" Obviously, if the display is to be legible and yet economical of space, some kind of compromise must be made. As Whitham (1964) has pointed out, if the characters are too small to be read or take an inordinate amount of time for observer processing, the display is of little use; and if the characters are too large, the display cannot hold sufficient data for most operational needs. Further, if the apparent size of characters is too great, details of character structure and visibility of slight distortions become objectionable. Finally, it can be assumed that, if the display area is enlarged to accommodate more huge characters, the observer's performance will fall off because he can no longer adequately handle the visual field.

Whitham (1964) defined 3.5 minutes of arc as the lower limit of character recognition, 10 minutes as the lower limit of character size for practical use in displays, and 50 minutes of arc as the upper limit. Because it has too often been the practice to design visual displays with computer capacity more in mind than the limitations of the observer, the problem of "too-large" symbology rarely occurs in the operational display.

It may also be assumed that contrast interacts significantly with character size (Howell and Kraft, 1959). Possibly color, intrinsically involving differential brightness contrasts, may also influence any size recommendation. Conversely, restriction of character size may have a bearing on recommendations regarding the use of color coding and the maximum number of useful colors. The occurrence of difficulty of color discrimination for small targets is well documented, and the chromatic aberration of the human lens indicates observers should have trouble identifying small short-wavelength hued characters.

The display situation, as it exists today, relies on a variety of character sizes, based on the available room for a screen, the display layout, and the total number of characters that must be placed on the screen to accommodate the user's possible need.

The problem has been attacked experimentally for the observer's requirements. Howell and Kraft (1959) examined the effect of several variables, including character size, on the legibility of non-color-coded symbols. Of the four levels of sizes examined, 6, 16.4, 26.8 and 36.8 minutes of arc, 26.8 was selected as optimum, with 36.8 showing little improvement in legibility, and, under a few conditions, some degradation of subject performance.

Several studies by the Mitre Corporation have indicated 16 minutes to be the practical lower limit for televised symbol identification (Marsetta & Shurtleff, 1966).

It has appeared desirable to examine the effect of apparent size of characters on the utility of color-coding. Size may have significant influence on certain colors and may even influence selection of color filters.

4.2. Apparatus and Procedure

4.2.1. Equipment and Display Variables

The projection equipment, experimental task and display parameters were identical to that of the third study (Section 3), with the exception that, due to a mechanical failure of the film cooling system, power to the source was reduced to 50 amps, 16 D.C. volts, to preserve the life of the Kalvar film. Open-gate brightness was thus reduced to four foot-lamberts, with 0.33 foot-lamberts ambient illumination reflected from the screen. Exposure time for each slide on the screen was 12 seconds.

Filters used were the 516-581 and 516-595 pairs which had both produced superior subject performance in previous studies. Six alphanumeric randomizations were used, with colored symbols completely randomized, the only restriction being that each alphanumeric appear only once in each of the seven colors.

Apparent height of the character was the main variable. Subjects were required to respond standing, with their head in a chin rest. Distance from the subject's eyes to the center of the screen and the corresponding visual angle of the height of characters is given in Table 4.1. Unfortunately, the display area layout prohibited viewing distances greater than 34 feet. The characters, two inches high on the screen, were double-size 465L standard symbology with a height-width-stroke width ratio of 4:3:1.

Table 4.1.

Distances of Subject from Screen Center and Corresponding Visual Angles

Distance in Feet/Inches	Visual Angle in Minutes of Arc
33'9"	17
28'8"	20
24'11"	23
22'	26
19'9"	29
17'11"	32

4.2.2. Subjects

Subjects were six college students with normal color vision and acuity, as defined by the criteria cited in section 2. They were part of the sample used in section 3 and in Rizy (1966) and were considered well-trained.

4.2.3. Experimental Design

A three-way 2 x 6 x 7 partially repeated measures design was used (Winer, 1962, Case I). Three of the subjects viewed displays produced by the 516-581 filter pair and three saw displays with the 516-595 set, the unrepeated factor.

All subjects viewed at all six distances and saw all seven colors at each distance. The six slides were presented in serial order six times to each subject. Distances were presented to each subject in a latin-square order, so that each distance was viewed with each slide once and at one of the six trials within each of the six sessions. Subjects read as many alphanumerics as possible within the time limit for each of the coding colors in the order: white, red, green, blue, yellow, magenta, and cyan.

4.3. Results

An analysis of variance for the 2 x 6 x 7 design with the last two factors completely repeated was calculated and is summarized in Table 4.2. Differences between coding colors were significant. The differences in sizes were highly significant, and the interaction of colors and sizes was significant. No differences were detected between filter pairs, either as a main effect or in interaction with the other two factors, size and coding colors.

Table 4.2.

Summary of Analysis of Variance of Data on Apparent Size Effect

Source of Variance	d.f.	Mean Square	F-Ratio	Probability
Between Subjects	5			
Filter Pairs (F)	1	5,676.25	<1.00	n.s.
Subjects within groups	4	18,367.48		
Within Subjects	246			
Apparent Size (S)	5	11,068.17	36.16	<.001
F x S	5	25.99	<1.00	n.s.
S x subj w groups	20	306.11		
Coding Colors (C)	6	8,817.99	6.36	<.01
F x C	6	129.48	<1.00	n.s.
C x subj w groups	24	1,387.04		
S x C	30	110.61	2.86	<.01
F x S x C	30	20.93	<1.00	n.s.
S x C x subj w groups	120	38.71		

A linear relationship appeared to exist between subject performance and distance from the screen (Figure 4.1), at least as high as 26 minutes of arc. In a further analysis into separate coding colors, Figure 4.1., all coding colors except blue indicated a decreasing slope before the maximum visual angle used was reached. Another part of the significant color by size interaction appeared to be due to reduction in variability of the coding color plots, in Figure 4.1., at the highest symbol size. At 32 minutes of arc there was a difference of less than four characters per trial between the highest code, yellow, and the lowest, blue, whereas at smaller symbol sizes a range of eight units was common.

4.4. Discussion

Overall performance increased by 50 percent when the visual angle of the characters was increased from 17 to 26 minutes of arc (i.e. a viewing distance change from 34 to 22 feet). A change in the visual angle from 26 to 32 minutes of arc (22 to 18 feet viewing distance) produced an improvement of only seven percent. One explanation of this diminishing return phenomenon might be based on the simple geometry of the situation. The former represents an increase in visual angle of more than 50 percent, while the latter involves a visual angle increment of less than 25 percent. An alternative, or perhaps complementary, explanation is that this range of apparent sizes is, or is approaching, the psychophysical area of diminishing returns. It may be recalled that Howell and Kraft (1959) found little improvement between 26.8 and 36.8 minutes.

The interaction of filter pairs and visual size was not significant, indicating that no difference between the 581 and 595 red filters occurs as a function of symbol size. While this is reassuring with regard to previous recommendations, the possibility of interaction should not be discounted until other filters have been tested. It is feasible to suppose that a blue filter lower in cutoff than the recommended 512-516 area might produce negligibly poorer symbology at 26 minutes of arc, but at 17 minutes or less, blue and possibly green and cyan might become wholly inadequate.

4.5. Conclusions

The customary recommendation found in psychological and human factors literature regarding apparent size---between 20 and 30 minutes of arc, and probably most satisfactory at 26-27 minutes---was supported for the seven-color display. Where colors must appear smaller than 27 minutes, it becomes questionable whether all seven colors will be legible, even in low ambient. Where constraints on character size are severe, it is perhaps wisest to abandon a seven-dimension color code and use colors that will maximize legibility, i.e., the brightest-appearing and sharpest (long wavelength) hues: white and yellow, red and magenta. Chromatic aberration of the human lens and consequent blurring of the visual image are minimal until the shorter wavelengths (e.g. blue and cyan) are approached.

When seven colors are required, however, adequate visual size of symbols must be maintained. It is readily recognized that this may be no easy feat

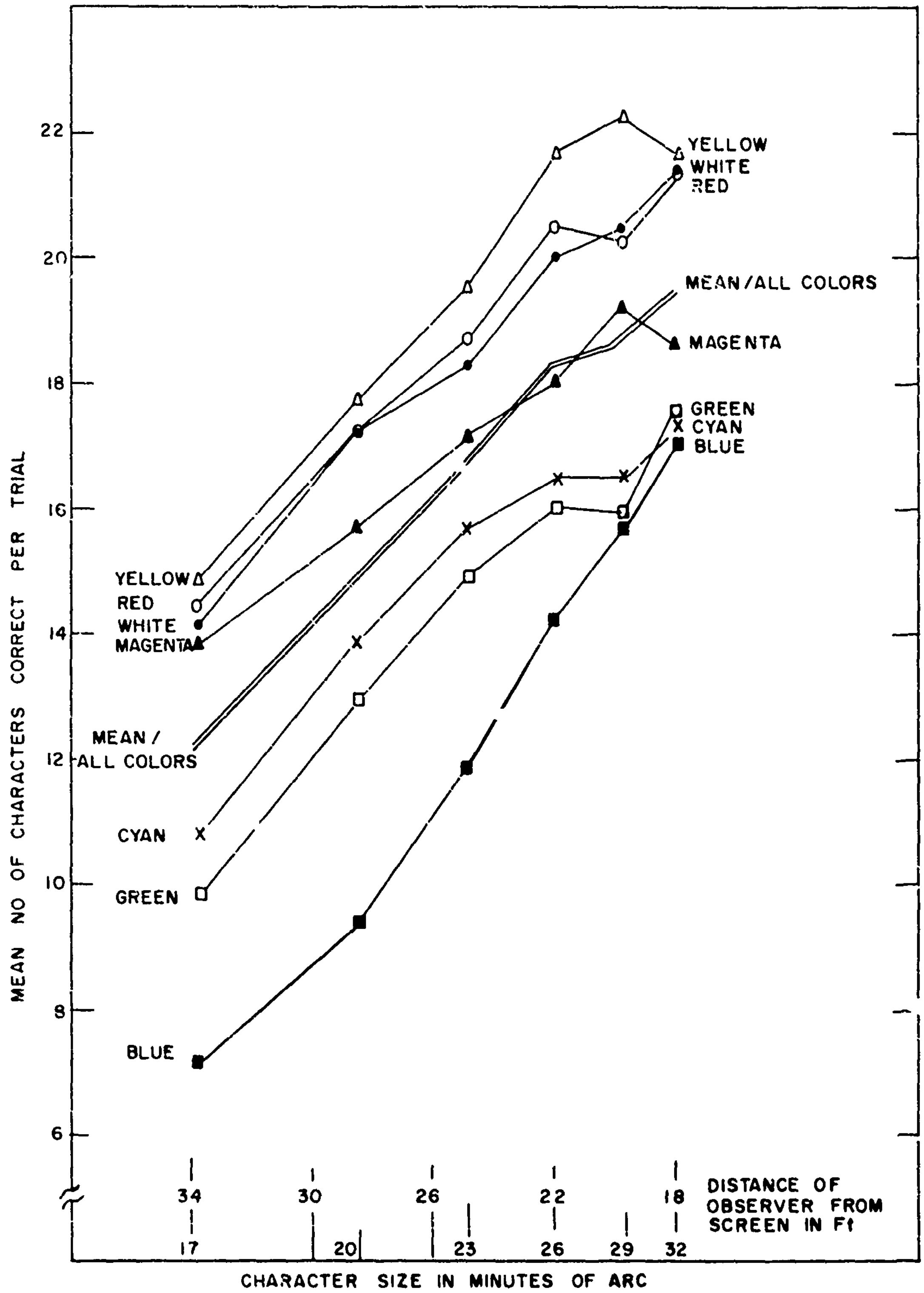

Fig 4.1 Subject Performance in Reading Color-Coded Alphanumerics as a Function of Size and Color

in an operational display room, where many people are working and all must have access to the data. However, the findings of this study strongly support the viewpoint that tradeoffs should involve layout of the environment, screen size, throw distance, display data capacity, and display brightness rather than character size. Obviously, savings in any of these will be of little use if the most distant essential personnel cannot interact effectively because they cannot read the display.

5. EFFECT OF BRIGHTNESS CONTRAST ON THE READABILITY OF A SEVEN-COLOR DISPLAY

5.1. Introduction

5.1.1. The Contrast Problem

A recurring problem in display research and in operational display specification has been to determine the desirable amount of brightness contrast between characters and the display background. Display character brightness is quite obviously a function of the luminous intensity emitted by the display or reflected from its surface. In the additive color projector, the luminous intensity is determined by the capacity of the light source, the power level to the source, the number and types of filters in the optical system, and the transmittance of the film in its undeveloped portions. The background is determined by the relative opacity of a film medium or amount of noise in a television image plus the amount of ambient light present in a display environment and reflected from the viewing surface. Roles will also be played by screen characteristics, particularly the directionality of their reflectance, and the state of sensitivity of the eye when the observer must alternate between bright and dim visual fields.

Display character brightness has not been a serious limitation on film systems, particularly with the introduction of high-power sources such as the 5 kw xenon lamp. Brightness has been a problem for newer techniques such as light-valve projection and electroluminescent panel displays and has appeared to be one of the reasons film systems have not become obsolete.

Ambient lighting control has been a general long-term problem area. Since any operational display area is essentially a work area, high light levels are required. Ambiently illuminated surface-color displays such as handwritten messages, printed matter and even face-to-face communication, demand some minimal ambient light intensity to be effective at all, and a higher level to proceed comfortably. On the other hand, projected or self-illuminated displays require some relative brightness differential to be legible. Obviously, some compromise must be made between optimum work area ambient---somewhere between 70 and 100 foot-lamberts---and the optimum ambient level for projected or luminous displays---something above zero ambient. Since the major element of background brightness is amount of light reflected from the display surface toward the observer, such techniques as rear-view screens, anti-reflective coatings, hooded screens and directional ambient lighting have been used in display settings.

What is desired for displays is a specification of, or even a feeling for, the maximum and minimum allowable contrast level for the various types of displays, beyond which the observer-display interaction begins to degrade. Secondly, it is desirable to explore the gray region, around the tolerances--particularly the minimum--to observe what happens to usefulness of color codes and the specification of dichroic filters, the author's major purpose. The maximum point is really of interest only to the system designer, as too high contrast has been dealt with operationally by turning down the power to the source. Finally, new techniques, which have been suggested to handle the contrast problem, should be evaluated to determine whether they provide an appreciable improvement.

5.1.2. The Operational Situation and a Survey of the Literature

A wide range of contrast specifications can be found in present-day systems, ranging from a 5:1 contrast ratio to 60:1 or higher. As the primary determiner of contrast has apparently been the particular type of display device involved, it would seem that everyone has been forced to live with whatever contrast is available. The question of what is the ideal contrast value for reading luminous symbology, such that it might serve as a valuable criterion for the selection of display techniques, has largely been ignored.

The standard contrast-visibility function derived by Blackwell (IES Lighting Handbook, 1959) is shown in Figure 5.1. A prominent feature of this curve is the regular decrease in contrast needed with increases in target brightness. The Blackwell curve has been adjusted to be applicable to practical tasks and to produce high operator accuracy.

The Blackwell curve indicated that in the normal range of character brightnesses of 5 to 35 foot-lamberts, a contrast of from 1 to 0.7 should be adequate for 99 percent observer accuracy. Contrast, as used by the IES, has been defined as $B_t - B_b / B_b$, where B_t is the target brightness and B_b is background brightness. It is assumed that target brightness is measured with the normal ambient incident on the screen, thereby justifying the subtraction operation and eliminating minus values.

One study which investigated contrast as one of several factors affecting the legibility of alphanumerics (Howell & Kraft, 1959) identified a small but highly significant difference in favor of high contrasts, up to 37.3, over lower contrasts, down to 12.1. A significant interaction of contrast and character size was also observed. The graphed data indicated that the smallest difference between subject performance at the two contrasts happened at 26.8 minutes of arc.

An attempt was made to compare the Howell and Kraft conclusion with the Blackwell function. Contrasts at two target brightnesses were plotted in

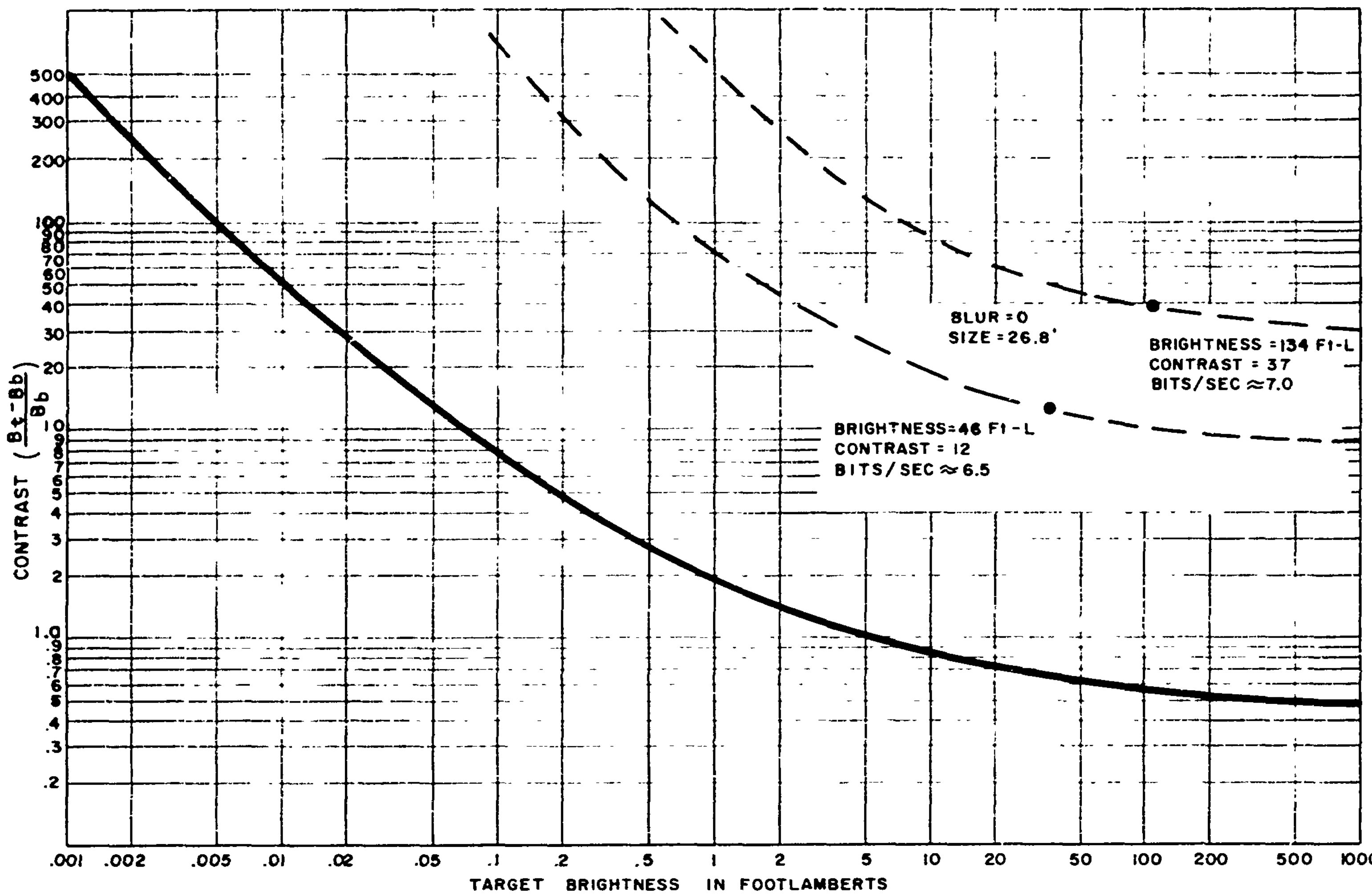

Fig 5.1 Brightness Contrast Function for Practical Tasks

(fr. IES Lighting Handbook, 1959; Hypothetical Curves for symbol identification at two levels of observer accuracy, based on data from Howell and Kraft (1959), are shown by dotted lines above the Blackwell curve.)

Figure 5.1 and served as anchoring points for hypothetical curves of symbol identification at two levels of subject performance. It would appear that Blackwell's "practical task" curve is too low for operational symbol identification even under excellent conditions of image sharpness and apparent size.

The effect of contrast upon display readability in the multicolor case is largely unknown. Where just one-color symbols are used, manipulation of the contrast variable is straightforward and legibility is the only concern. Multicolor displays complicate the contrast-measurement and also introduce the problem of color discrimination into evaluation of contrast.

An overall index of display contrast, in some way describing the heterogenous color brightnesses involved, would be highly desirable. One way of stating the contrast level, frequently done in systems work, is to state the contrast ratio of the white symbol to the background. Several objections may be made to this practice. Brightness measurement in an operational system is still a pretty primitive procedure, and questions are frequently raised concerning the validity and reliability of readings. Two apparent sources of error exist in the present system: variability due to stroke variations and variability due to differences from slide to slide.

It has been frequently observed, while measuring brightness within the stroke width of a character, that wide fluctuations occur when the fixation point of the device is moved from place to place within the stroke. Further, it seems that characters occupying greater area give higher brightness readings; "W" and "M" are generally a good deal brighter than "I" or "J." As an example, sizeable brightness variation has been observed both within slides and from slide to slide in the 465L-type system used.

The solution proposed is to eliminate the film and measure the screen brightness with the projector "open-gate," allowing the experimenter to integrate over a wide area and be free of character or slide anomalies. The expression, C_D, display contrast, was selected:

$$C_D = \frac{B_t - B_b}{B_b}$$

where B_t is the open-gate brightness as reflected from the screen to the observer's position with normal ambient falling on the screen; and B_b is the ambient brightness as reflected from the screen and likewise measured from the observer's position.

In the general case, the use of colored symbols reduces the amount of contrast needed (Poole, 1966). Since the use of filters also reduces the brightness of the symbols, brightness contrast is simultaneously reduced. The percent savings, unfortunately, is not readily estimable. A recurrent suspicion in the dichroic filter studies has been that contrast will affect

the relative efficiencies of coding colors (Rizy, 1965). Whether or not total subject performance, all colors combined, will change in the midrange of contrasts is another question.

Two studies have been accomplished, one dealing with the midrange of display contrasts, from 10 to 40, to examine the overall effect of contrast and its interaction with coding colors. The second investigation compared contrasts below 10 in factorial combination with filters, to assay the question whether contrast would affect filter specification.

5.2. Color Coding as a Function of Contrast

5.2.1. Apparatus and Procedure

A fluorescent desk lamp with two 15-watt tubes was situated in front of and below the display screen. The shade prevented bare lamps from falling in the observer's field of vision. The reflected lamp light was measured as 1 foot-lambert in the center of the screen with a maximum falloff of 10 percent at screen corners. The other display parameters, experimental task, and display equipment were the same as in the third and fourth studies. A blower fan was installed below the film gate to keep the Kalvar film from bleaching out when high power levels were applied to the lamp.

Power inputs selected were 45 amps at 17 D.C. volts, 65 at 19, 83 at 20.5 and 100 at 22, producing measured open-gate brightnesses of 11, 21, 31 and 41 foot-lamberts respectively (including ambient). Display contrasts, as defined above, were 10, 20, 30 and 40.

Subjects were three college students who had already observed the display in eighty trials during other experiments. They sat five degrees off the projector-screen axis and 22.5 feet from the screen. Visual angle subtended by the characters was 27 minutes of arc at the subject's viewing position. Filters used in the projector were the 516 blue and 595 red dichroics, previously defined as adequate. Misregistration was kept below 35 percent. Four randomizations of the alphanumeric matrix were used. Display contrasts were presented to subjects in a Latin square, and slides were shown serially. Exposure time per trial was controlled at 15 seconds.

5.2.2. Results

Average performance by subjects on each color code at each contrast is shown in Figure 5.2. A readily observed difference may be perceived among coding colors, as well as some possible interaction with contrast level. The data did not meet the assumptions of homogenous error variance in color codes, so an overall parametric test was not used. A non-parametric analogue, the Friedman analysis of variance by ranks (Siegal, 1956), tested the main effect of display contrast for significant differences. A χ^2_r of 8.2 was obtained, with a probability of chance occurrence of .017, indicating high probability that real differences occurred in the three subjects' performance over the range of display contrasts used. The contrasts giving highest performance were 20 and 20, with 40 generally lower and 10 being the poorest contrast, in terms of subject performance.

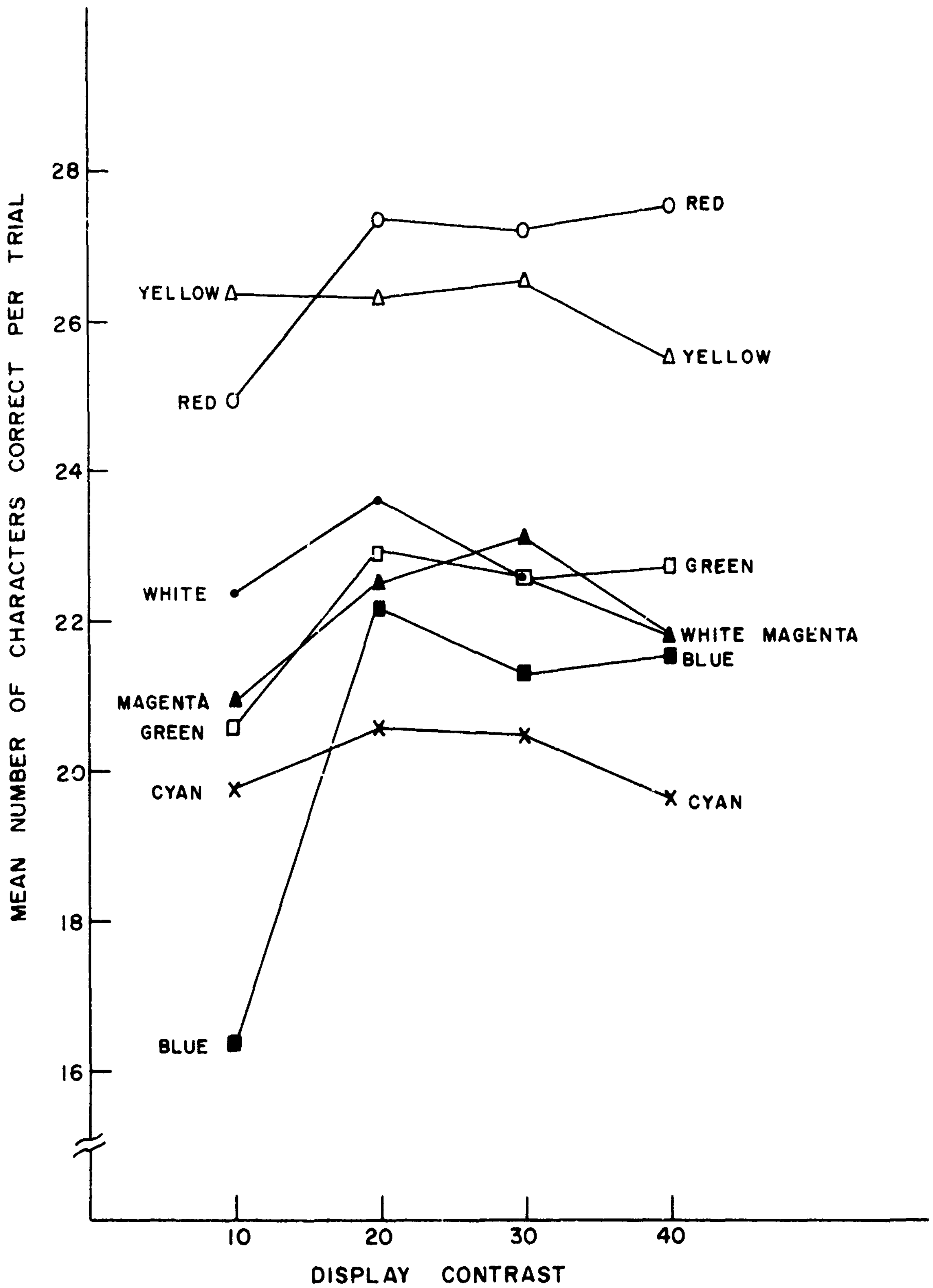

Fig 5.2 Reading Performance for the Seven Color Codes as a Function of Contrast

The effect of contrast on each display color was also tested statistically, using a parametric technique: one classification repeated-measures design (Winer, 1962), and the non-parametric Friedman. Summary of results is shown in Table 5.1.

Table 5.1.

Results of Tests of Significance
for each Coding Color at all Contrasts

Coding Color	Parametric Test				Nonparametric Test	
	MSa	MSe	F	p	χ_r^2	p
White	28.11	6.36	4.42	.10	5.5	.16
Red	70.97	4.56	15.56	.01	5.8	.15
Green	54.89	9.14	6.01	.05	5.8	.15
Blue	344.97	97.14	3.55	.10	5.8	.15
Yellow	11.22	6.56	1.71	n.s.	5.5	.16
Magenta	45.45	33.41	1.36	n.s.	3.1	.47
Cyan	11.56	23.87	.48	n.s.	1.3	.83

Only the first four colors listed indicated significant differences over contrasts with the parametric test. Due to the low number of subjects and observations and the rather exploratory nature of the investigation, a relatively high significance level of .10 was adopted. Responses in the red, green and blue categories improved with higher contrast; white appeared to improve from 10 to 20 contrast, then become poorer as contrasts became higher.

Results of the Friedman test paralleled the parametric test, although the obtained probabilities leaned more in the direction of chance occurrence of events. This was interpreted as being due to the small sample size and, consequently, small amount of power in the test relative to the parametric method.

5.2.3. Discussion and Conclusions

The optimum range for display contrast when a seven-color display is being used and background brightness is on the order of one foot-lambert is apparently in the region of 20 to 30. This may be converted to the conventional contrast of white symbol to background. Since the white symbol is about 60 percent as bright as open-gate, due to absorption or scattering in the clear section of the Kalvar film (data from Snadowsky, Rizy and Elias, 1964, repeated recently), the desirable contrast of white symbols should fall around 12 to 18, which is within the range of operational values.

An open-gate contrast of 10 (white symbol contrast of 6) is probably too low since red and green are somewhat degraded and blue becomes much more difficult to read. A contrast of 40 (24 for white symbol contrast) appeared to be the level where white began to appear too bright or to "bloom." It is expected that, much above 40, performance in yellow might also begin to decline.

Where display brightness and background brightness are considerably different from those used here, the optimal display contrast range will probably vary. Extrapolating from Blackwell's general function, it may be concluded that with higher brightnesses, display contrast may be reduced slightly. With much lower brightnesses, much greater contrasts should be required.

5.3. Effect of Filters and Coding Colors on a Low-Contrast Display and an Experimental Comparison of Additive and Subtractive Color

5.3.1. Discussion of Problem

The previous study indicated that the optimum display contrast for character readability was between 20 and 30. An examination of L-system documentation indicated, however, that a large number of group displays and consoles are using a 10:1 contrast ratio and that a few are using display contrasts of less than 10. Further, the need for sufficient ambient to read hard copy appeared widespread; so it was likely that operational displays would encounter high ambients rather than low in the present and future. It seemed advisable to examine at least one dimension of filter specification under low contrasts, to determine whether contrast is an influential factor in filter specification.

A second concern was to amplify and examine the changes in color code readability found at low contrast levels in the previous study. It had been indicated that red would deteriorate faster than yellow at low contrasts and would result in consistently poorer subject performance. Also, the utility of blue as a coding color would be severely diminished.

Finally, it seemed appropriate to include a comparison of additive with subtractive color. The basic technique of color addition has been explained earlier in this series of reports (Rizy, 1965) and may be found in any thorough exposition of current display techniques. The underlying principle is recounted as a matter of course in any basic psychology text. Subtractive color has lately found favor as a possible display technique (Poole, 1966). It is used in a preliminary stage of the 465L display system, although it is not used directly in any known display.

The initial step in the construction of a 465L display is the photographing of symbols from a character generator onto silver halide film. The negative of the desired display is then contact-printed on Kalvar UV-sensitive film, producing a positive of the silver halide negative for the final display. At the last stage the film is then used to project light characters on a dark background.

If, however, the silver halide film were to be used in the projector, one form of subtractive color would be demonstrated. Here the projector beams a white field onto the screen. Characters on the film field are opaque, instead of clear in the additive approach. Hence, these characters subtract that component of white in the film field's corresponding optical channel. An opaque character in the projector's red channel film field will

produce a minus-red (or cyan) character on the screen. A character in the green channel will appear on the screen as magenta, and a minus-blue character is yellow.

Registering these subtractive primaries on the screen will produce the additive primaries, red, green and blue. (Minus-blue and minus-green, minus-blue and minus-red, and minus-green and minus-red, respectively). Overlapping all three subtractive images will eliminate all projector brightness (except for minimal transmission through the opaque portions) and produce a black symbol. In summary, seven colors on a white background are available in the subtractive process: the primaries yellow, magenta and cyan; the two-primary reductions red, green and blue; and removal of all three primaries, or black.

Certain merit exists favoring subtraction over addition. One of the largest faults in the film display application is film cost, and the subtractive approach lowers the cost. The complexity of the processing system is reduced. The brightness of the display background is a noticeable increment in ambient illumination in low ambient environment and may slightly increase the legibility of hard copy. Finally, the possibility exists that subtractive displays are more legible in high ambient.

Several countering points may be made. Such a system does not permit map overlays (although, conceivably, the subtractive display might be projected directly onto maps themselves). The white background is subject to interference where the black background is not. If dust gets onto the film or into the optics during projection, the foreign material subtracts color from the field just like a symbol image would and appears as an amorphous color image on the screen. In the additive case, gradations in the "blackness" of the background cannot be detected by the observer and do not distract him.

These factors mentioned above might limit the use of subtractive displays to special situations. The basic evaluation of subtractive color in displays hinges on the question of symbol legibility and color discrimination. Research on projected color comparing white and black backgrounds was not found in a literature search preceding the color filter task. This study has been designed to provide that information for the low contrast condition.

5.3.2. Apparatus and Procedure

5.3.2.1. Equipment and Display Variables

The additive color projector and accessory timing equipment previously used and described were the main devices used. Two power settings produced the brightness differential: 50 amps, 17 D.C. volts to the 2.2 kw xenon source (9.5 foot-lamberts reflected open-gate brightness in ambient at screen center); and 75 amps, 20 D.C. volts (16.5 foot-lamberts open-gate in ambient). Ambient was measured at 2.5 foot-lamberts coming from the screen and was produced by fluorescent lighting in the viewing area and in an area behind the screen. Display contrasts were 2.8 and 5.6 respectively.

The viewing area was well lighted to simulate conditions for easy reading of hard copy. A freshly prepared magnesium oxide block reflected a measured 70 foot-lamberts, as measured by a Spectra spot photometer. The observer sat 43 feet, six inches from screen center, and characters subtended 23 minutes of arc.

Contact prints of eight additive color slides were made, giving the opaque characters on clear fields needed for subtractive projection. While it would have been more desirable to use the original silver halide film from which the additive prints were made, these were not available. It may have been that artificial degradation was introduced on the subtractive slide by the second copying process, but this risk was taken as the unavoidable outcome of the situation. Brightness measurements taken on the white and black symbols and their respective backgrounds indicated that contrast was six percent less on the subtractive display, and it was concluded that contrast differences were not large enough to significantly affect legibility.

The dichroic filters used in the study were two blue filters, one cutting off 50 percent of the light at 498 nanometers (nm), the standard 465L blue filter, and the other cutting off at 516 nm. The latter filter was previously identified (Rizy, 1965) as being related to subject performance superior to that with the 498 filter. These two filters were separately paired with a red reflecting filter cutting off at 595 nm, the 465L red filter, to give two sets of seven colors in the experiment.

5.3.2.2. Subjects

Eight male college students were used as subjects. They had no previous experience in display research but had normal acuity for far vision, between 20/17 and 20/25, and normal color vision as measured by the Bausch & Lomb Orthorater. They were given four practice trials with the display to learn the experimental task and become familiar with the color codes. The standard 465L dichroic filters were used for practice.

5.3.2.3. Experimental Design

A 2 x 2 x 2 x 2 x 7 factorial design was used, with one nonrepeated and four repeated measures. The nonrepeated factor was order of color codes read. One group of four subjects always read color codes in the order: white (black), red, green, blue, yellow, magenta, cyan. The other group read in the reverse order.

The four completely repeated measures included two types of transparency, the Kalvar, henceforth called the additive display transparency, producing colored symbols on a black background; and the silver halide contact print, called the subtractive display transparency, producing colored symbols on a white background.

There were two levels of display brightness, 9.5 and 16.5 foot-lamberts open-gate, with display contrasts of 2.8 and 5.6, respectively. Two pairs of dichroic filters were used, the 498-595 and 516-595 pairs. Finally, there were seven colors. In the additive case they were white, red, green,

blue, yellow, magenta and cyan. In the subtractive display white became black.

5.3.3. Results

The data were analyzed by preliminary tests which supported the suitability of a parametric test. A five-factor analysis of variance for partly repeated measures was calculated and is summarized in Table 5.2.

Table 5.2.

Summary of Analysis of Variance of Brightness, Filters, Colors, Transparency Type and Color Order Effects

Source of Variance	d.f.	Mean Square	F-Ratio	Probability
Between Subjects	7			
Order of Colors (O)	1	2,815.02	.53	n.s.
Subjects within groups	6	5,290.85		
Within Subjects	440			
Transparency Type (T)	1	36,811.87	59.49	< .01
OT	1	227.15	.37	n.s.
T x subj w groups	6	618.74		
Brightness (B)	1	15,687.05	55.22	<.01
OB	1	11.90	.04	n.s.
B x subj w groups	6	284.06		
Filters (F)	1	1,526.62	20.16	<.01
OF	1	13.93	.18	n.s.
F x subj w groups	6	75.73		
Coding Colors (C)	6	17,216.59	56.35	<.01
OC	6	247.46	.81	n.s.
C x subj w groups	36	305.55		
TB	1	256.53	3.13	n.s.
OTB	1	6.74	.08	n.s.
TB x subj w groups	6	81.88		
TF	1	202.24	2.84	n.s.
OTF	1	.11	.01	n.s.
TF x subj w groups	6	71.31		
TC	6	31,242.53	60.35	<.01
OTC	6	138.81	.27	n.s.
TC x subj w groups	36	517.70		

(Cont'd)

Table 5.2. (Cont'd)

Source of Variance	d.f.	Mean Square	F-Ratio	Probability
BF	1	.65	.02	n.s.
OBF	1	53.63	1.54	n.s.
BF x subj w groups	6	34.80		
BC	6	412.26	11.76	<.01
OBC	6	31.92	.91	n.s.
BC x subj w groups	36	35.07		
FC	6	243.12	8.36	<.01
OFC	6	43.01	1.48	n.s.
FC x subj w groups	36	29.09		
TBF	1	29.51	1.72	n.s.
OTBF	1	13.94	.81	n.s.
TBF x subj w groups	6	17.13		
TBC	6	213.96	7.05	<.01
OTBC	6	15.33	.51	n.s.
TBC x subj w groups	36	30.34		
TFC	6	101.28	2.94	<.05
OTFC	6	17.69	.51	n.s.
TFC x subj w groups	36	34.45		
BFC	6	58.46	3.68	<.01
OBFC	6	19.57	1.23	n.s.
BFC x subj w groups	36	15.89		
TBFC	6	14.15	.66	n.s.
OTBFC	6	1.79	.08	n.s
TBFC x subj w groups	36	21.50		

Order of colors was not significant as a main effect, nor did it interact significantly with any other factor or combination of factors. The order factor was thus irrelevant in the experiment and was disregarded.

The main effects of transparency type, brightness, filters and colors were all highly significant. It was inferred that additive displays were read better than subtractive displays (mean subject score for additive was 12.9 characters correct per trial; for subtractive, 10.6). As might be expected, the higher brightness display (16.5 foot-lamberts, 5.6 contrast) was read more easily than the lower brightness display, with average subject scores being 13.0 and 11.0 respectively. The 516-595 filter pair was associated with slight but statistically significant higher scores than the 498-595 filter pair, 12.0 to 11.5. Significant differences also occurred among colors averaged over all other conditions.

This last main effect was in a way meaningless, because only in the loosest sense were there seven color categories. The appearance of a color was quite obviously a function of the type of background, and although subjects apparently had no difficulty in using the color names, their performance reflected the interaction of color with background.

A highly significant Transparency Type by Coding Color interaction was detected by the analysis. This interaction is shown in Figure 5.3. It should be noted that yellow gave the highest subject scores in the additive display and the lowest in the subtractive display. White-black and red differed little between the two transparency types. Blue improved substantially as a subtractive color, whereas performance on magenta and cyan symbols decreased. The "best" coding colors were decidedly a function of the type of transparency.

The brightness by color and the filter by color interactions were also significant; but, again, little can be said since each color name was represented in the experiment by two very different colors, and "average" performance in a color category would tell little about either color. Some of the underlying factors of explainable variation may be seen in the three-factor interactions.

The transparency by brightness by color code interaction was significant and appears in Figure 5.4. In the additive display, the blue color code was most affected by low display brightness, decreasing from 9.3 responses per trial to 5.5. The subjects' responses to red symbols also diminished by a large amount, from 14.9 to 12.6 per trial. Decreases in performance in the subtractive display were more uniform from color to color.

The transparency by filters by color effect was also significant, indicating that filters also influenced each color code's resistance to decreased brightness effects. As may be observed in Figure 5.5, there was a consistent difference between the 498 and 516 blue dichroics, except in one case, additive cyan. The largest difference between filters in the additive display was in the red color code. Improvements in the readability of the red code when high cutoff blue filters were used has been previously observed (Rizy, 1965, 1966). Three colors in the subtractive display appeared to be affected by filters. Specifically, a greater improvement per trial was noted in the black, blue and yellow codes.

5.3.4. Discussion

5.3.4.1. Brightness Contrast

The data substantiated the expectation that, at the relatively low contrasts employed, brightness and subject performance should be positively related. This was true of overall subject scores as well as in every color code and for both types of transparencies. Relating these findings for 2.8 and 5.6 display contrasts to those reported earlier in the chapter for contrasts of 10 and higher would be somewhat tenuous although certain consistencies may be found.

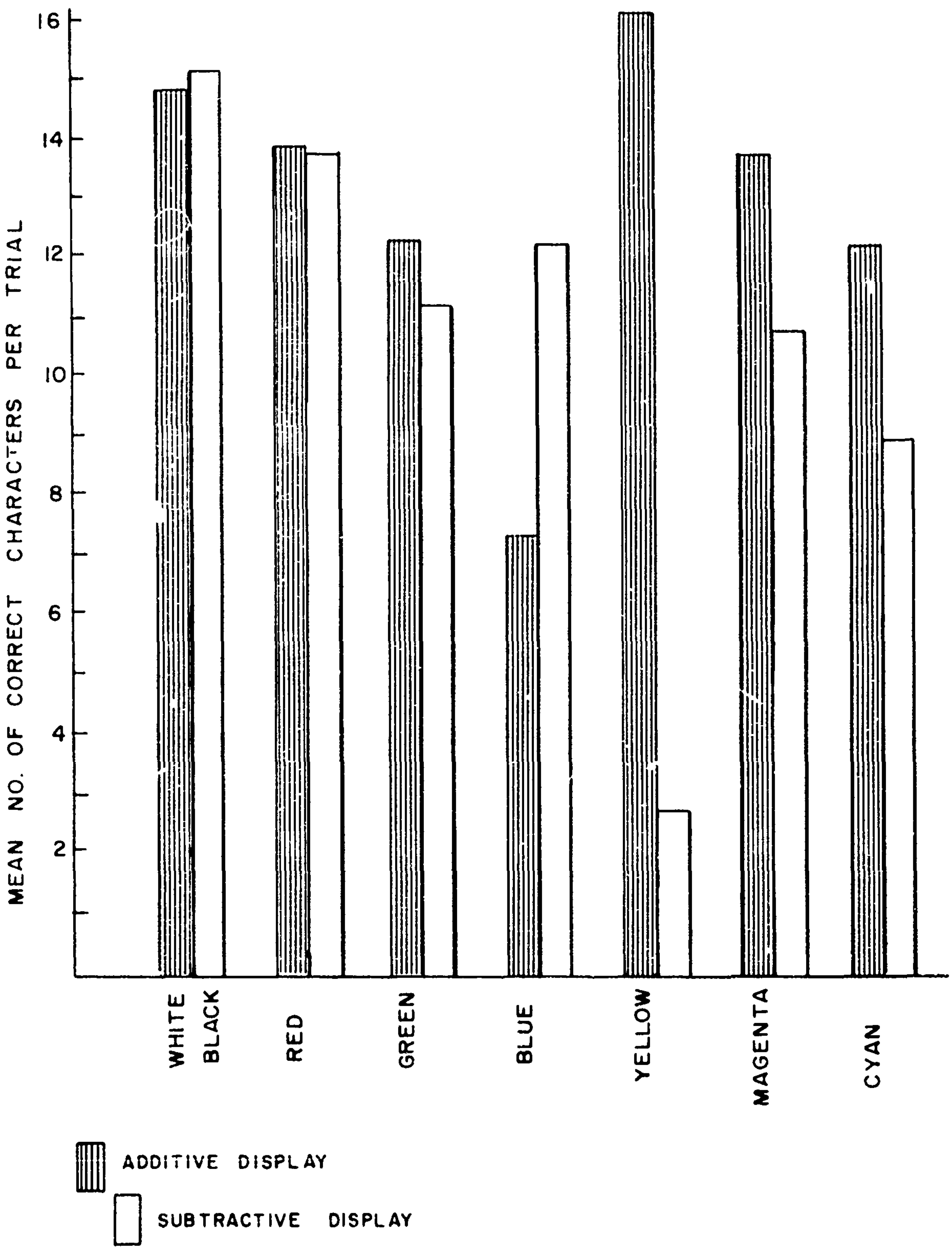

Fig 5.3 Relative Readability of the Seven Color Codes in Additive and Subtractive Displays

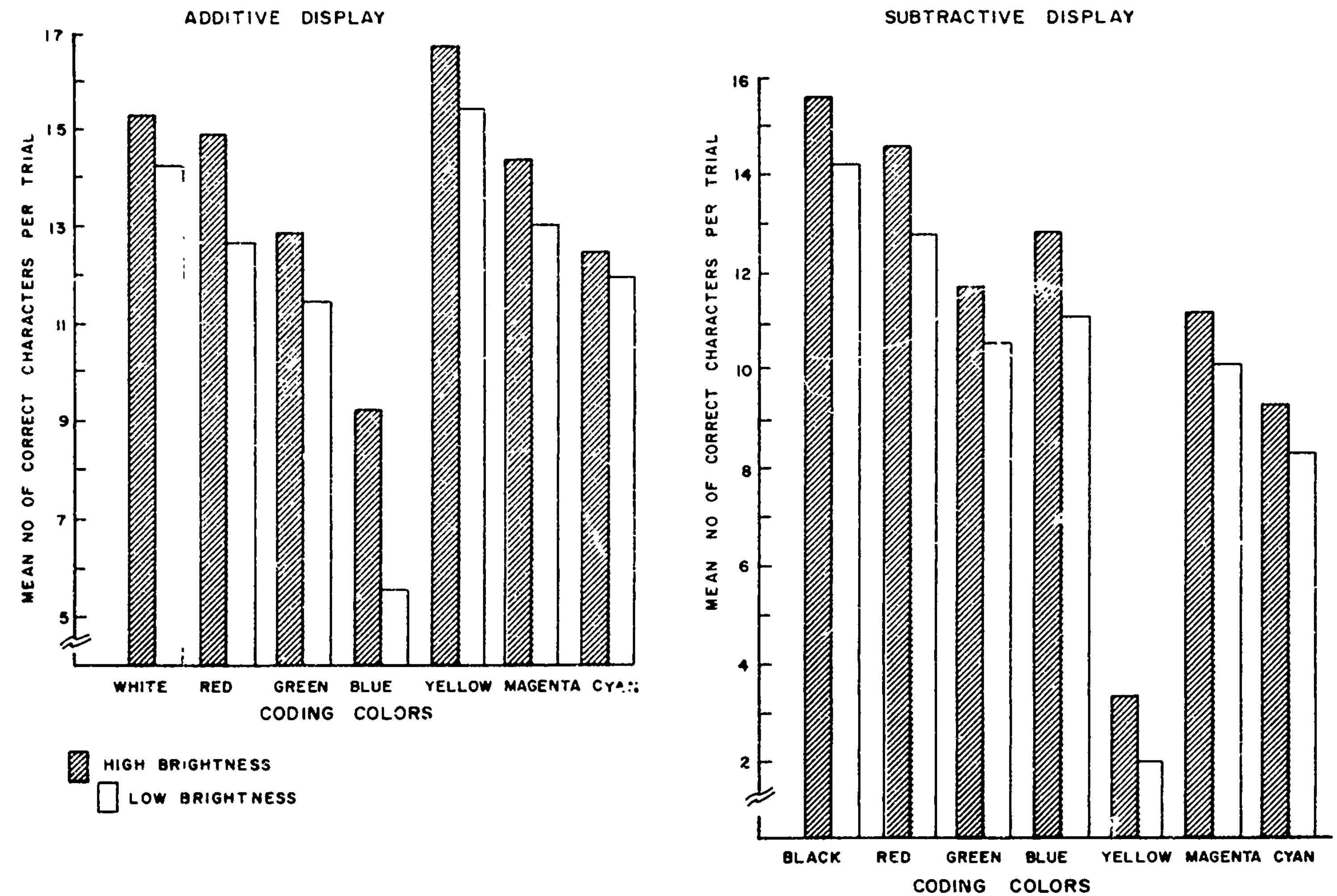

Fig 5.4 Performance on Each of the Color Codes at
Two Levels of Brightness

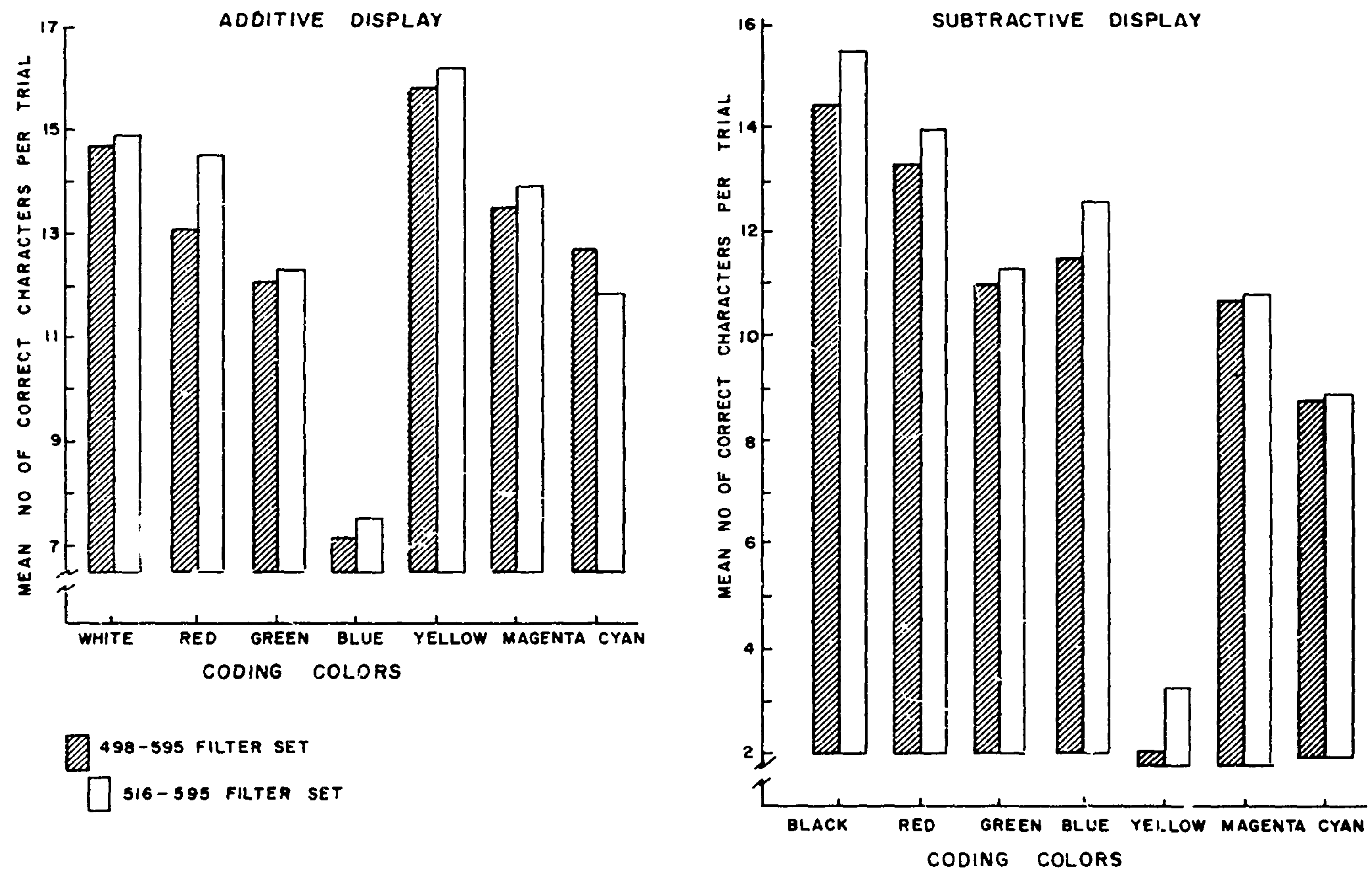

Fig 5.5 Performance on Each of the Color Codes as a Function of Two Different Pairs of Dichroic Filters in an Additive and a Subtractive Display

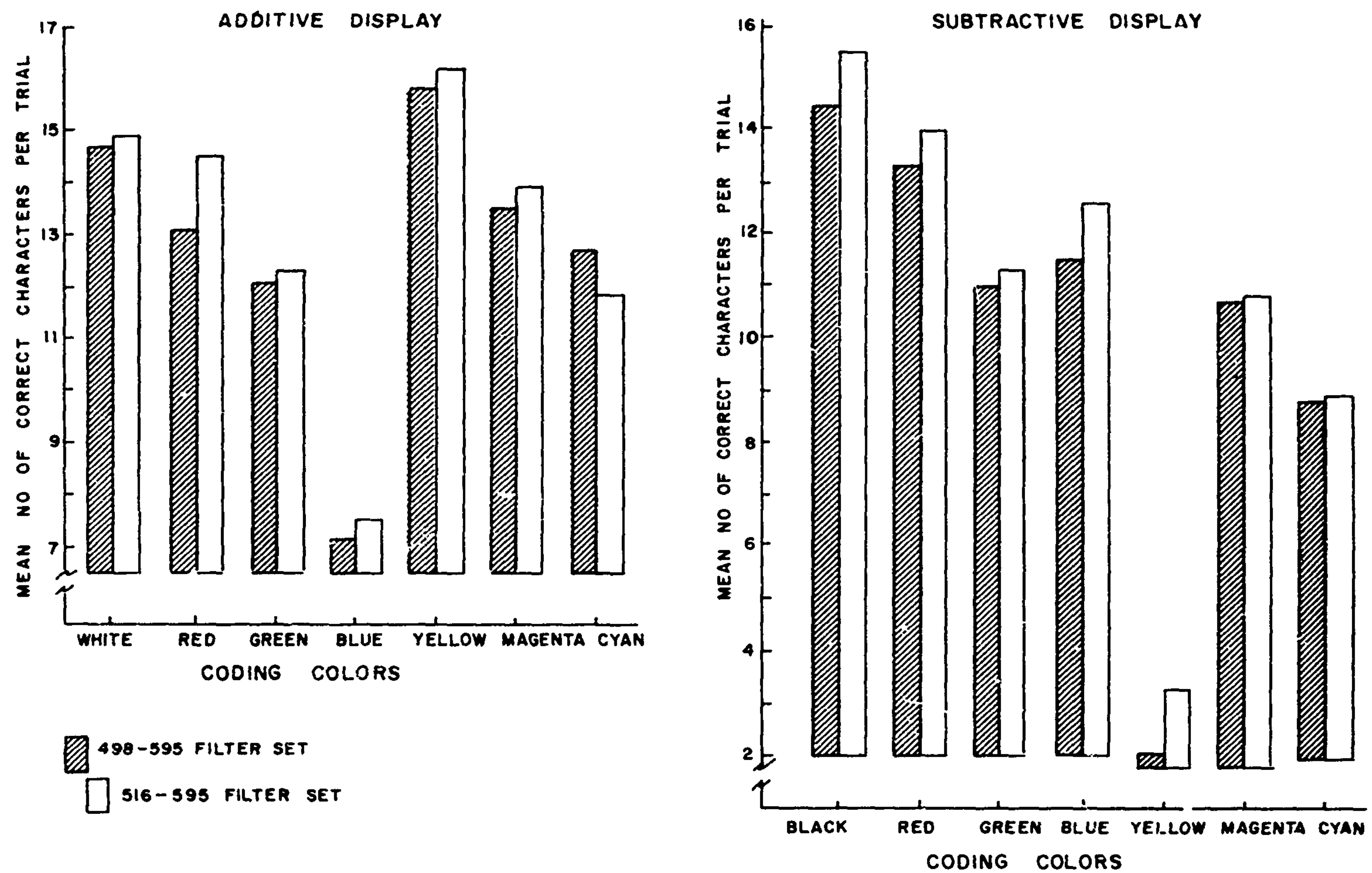

Fig 5.5 Performance on Each of the Color Codes as a Function of Two Different Pairs of Dichroic Filters in an Additive and a Subtractive Display

difference among filters has been attributed to the achievement of some optimal balance of the three primaries. The balance is in large measure explainable in terms of chromaticity and brightness (see Rizy, 1966, for a fuller discussion of pertinent color research), although borderline cases, e.g., the recurrent confusion between green and cyan, might appropriately be pursued in a more basic vision laboratory.

5.3.4.3. Additive Versus Subtractive Display

This issue appeared more fully resolvable than before. It had been suggested that subtractive color might be more readable under low contrast conditions. Only contrary evidence was uncovered here. Subtractive displays were read more poorly under both conditions of contrast and showed no trend of improving, relative to the additive display.

The subtractive approach might still be considered worthwhile for a six-color system, without yellow. It would probably prove satisfactory and certainly economical, provided the other constraints--no map overlays and a sealed, clean projection system--were met.

5.3.5. Conclusions

Subjects' reading performance continued to deteriorate below display contrasts of 10. Use of seven colors with a contrast below 10 is not recommended. Blue is particularly objectionable and should not be used for alphanumerics or other symbols.

Where a display system might have to operate under low contrast conditions at any time during its life, an additive technique is recommended over a subtractive approach.

The previous recommendation for blue dichroic cutoffs, at or about 516 nm, is supported.

With high contrast, the subtractive color process will probably give satisfactory results in six color codes, provided the optical system is kept clean and no map overlays are required. The 516 nm cutoff blue filter is also recommended for subtractive uses, in lieu of the standard 465L blue dichroic cutting off at 495 $\pm$ 7 nm.

6. GENERAL SUMMARY

This report covered the third and final series of experiments on the subject of filter specifications for color additive displays, utilizing a projector system similar to that employed in the 465L Command and Control System. In addition to the basic problem of dichroic mirror specification, several ancillary problems in multicolor display application were examined. The experiments conducted in this final phase of the effort may be summarized as follows:

6.1. Blue Filter Studies

Two experiments were performed to determine the upper tolerance level for blue dichroic filters with a precision greater than that developed in prior experiments and to generally refine the earlier recommendations.

The most reasonable expectation from using higher-cutoff blue filters was an improvement in the legibility of the blue color code. While blue did become brighter and green more saturated, these changes were not favorably manifested in subjects' performance. Responses to the green and blue codes did not improve with the higher-cutoff blue filters. Rather, cyan became quite similar to blue and magenta appeared quite unsaturated, leading to performance decrements in both magenta and cyan. The 512-516 nanometer range appeared to be optimal for the blue dichroic.

6.2. Order of Dichroic Filters in Projector

In the conventional color additive technique (e.g. the 465L Command and Control System) the blue filter is placed first in the optical pathway in order to compensate for the relatively low luminosity of the blue component of the white light source. This exploratory study reversed the order of the filters, with the red dichroic preceding the blue in the optical pathway. It was hypothesized that, while this ordering would produce a blue of much less brightness, enhancement of the other colors might be such as to make the technique desirable. Blue would, of course, still be retained, but as a background hue so that its color identification would not be critical.

Due to the lack of statistical significance, definitive conclusions with a high degree of confidence could not be made. While it is unlikely that any major changes in legibility of coded alphanumerics would result from such a filter switch, it would appear that some improvement in certain of the colors would ensue. For example, with the reversed order of filters, cyan appears to be a much improved color for coding purposes. Further research with the specific application of coding being defined would be necessary to resolve the problem.

6.3. Effect of Character Size on Legibility

While required symbol sizes (subtended visual angles) for black and white character/background relations have been well established, a question arises as to whether these criteria are adequate for the situation involving alphanumerics of various colors and luminosities, especially when they are to be employed simultaneously in the same display.

It was determined that the use of seven colors did indeed place constraints on acceptable symbol size. A lower limit of sixteen minutes of arc, as found in some of the published literature, was found to be inadequate for the situation examined here. A standard of 26-27 minutes was recommended from the results of this experiment. Where it is necessary to display characters of a smaller vertical dimension, it was further recommended that the full seven colors not be employed. Maximum legibility would be obtained by using colors of high luminosity such as white, yellow, red, and perhaps magenta.

Such a choice would also tend to minimize possible deleterious effects produced by chromatic aberrations of the human lens at the shorter wavelengths.

6.4. Effects of Brightness Contrast

While a considerable body of literature exists bearing directly on contrasts required for conventional black and white displays, standards for multicolored displays are less well defined. In the general case, the use of colored symbols reduces the amount of contrast required. Paradoxically, however, the use of filters to produce these colors reduces the brightness contrast. The value of the open-gate brightness needed in order that the gain due to color contrast effects will counterbalance the loss of brightness contrast resulting from the application of filters was the subject of these two experiments.

It was disclosed that the optimum open-gate brightness contrast for the equipment used was in the range of 20 to 30 with a background of one foot-lambert. Due to internal system losses and losses in the Kalvar film, brightness contrast for the white symbols ranged from about 12 to 18 for the optimal condition. It was found that at contrasts of ten or below, blue symbols became very difficult to read, while at contrasts of 40 or above white figures began to "bloom" and legibility was reduced.

6.5. Effects of Extremely Low Contrast

This experiment evaluated legibility effects for contrasts under ten. The effects suggested in the earlier experiments were further corroborated with contrasts of 2.8 and 5.6. For high ambient levels which might result in such contrasts, the use of seven colors is definitely not advisable. While the bright colors such as white and yellow still resulted in adequate legibility, both blue and red were unusable because they simply did not differ sufficiently from the background.

6.6. Subtractive Color System

As a result of suggestions from several sources, a technique was examined wherein negatives were employed in the projection system rather than positives. In this system the opaque character subtracts a component of white from its appropriate color channel. Thus, a character which would in the conventional system be white (red + green + blue) now becomes black (white-red-green-blue). Displays produced in this manner have colors somewhat similar to the conventional additive display, but the background is white and the seven colors of the characters include black.

In addition to logistic simplification as a result of eliminating the positive film stage, it was hypothesized that some visual gain might be realized, especially if less than the full seven colors were employed. The latter constraint follows from the expected loss in light due to the subtractive effects of the film negatives.

Generally speaking, few significant advantages of the subtractive technique were disclosed. Under low contrast conditions, it was decidedly

inferior. It is likely, however, that a subtractive technique would produce satisfactory results with sufficiently high contrast. In addition, a restriction to six colors (eliminating the weak residual yellow) should make a subtractive technique useful for special applications.

6.7. The "Ideal" Seven-Color System

All dichroic filters should traverse from 90 percent to 10 percent reflectance over no more than a 40 nanometer (nm) bandwidth. In the area of high reflectance beyond the point of inflection, reflectance should average no less than 95 percent and at no point be lower than 90 percent. In the area of low reflectance beyond the point of inflection, reflectance should average no more than 5 percent and at no point be higher than 10 percent. These requirements should hold for the effective visible spectrum as limited by ultraviolet and infrared filters, i.e., 425 to 700 nm.

The blue filter, placed first in the system, should have a 50 percent cutoff in the range of 512 to 516 nm. The red filter, placed second in the light path, should have a 50 percent cutoff between 580 and 595 nm. A minimum apparent height of symbols of 26 minutes of arc should be maintained for essential observing personnel. A display contrast of 20 to 30 should be obtained when ambient reflected from the screen is in the order of one foot-lambert. The white symbol-to-background contrast should be in the range of 12 to 18. Contrasts may be somewhat lower with much higher ambient levels.

6.8. Abridged Color Systems

Several "less-than-seven" color systems might be employed in specialized circumstances wherein the full seven color complement is not required.

For example, a six-color subtractive display (without yellow), might be used. The same recommendations for filters, apparent size, and contrast would hold. In addition to requiring particularly clean optics, no requirement for projected map backgrounds could be met. Such a system could result in a considerable saving in film costs.

A six-color additive display, omitting blue but improving cyan discrimination, could result from reversing the order of the dichroics to a red-blue arrangement.

A five-color additive system might be employed, omitting blue and red, where optimum contrast cannot be maintained.

A four-color additive system, using white, yellow,red and magenta (where small symbol sizes, below 26 minutes of arc, must be used), could also be employed.

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13. ABSTRACT

Specification of primaries for seven-color display generation was examined under a wide range of conditions, including modifications to the equipment, manipulation of environmental variables, and control of response variables. The basic purpose of this series of studies was to increase the precision of previously determined specifications for dichroic filters to be employed in additive multicolored large-scale displays. The upper tolerance limit for the blue dichroic filter was determined to a high degree of precision. In addition, questions of filter order, character size, and brightness contrast were examined experimentally to determine their influence on filter specification.

As a summary contribution, an "ideal" seven-color additive system is outlined. Finally, recommendations are provided for situations wherein physical restrictions militate against the employment of the full seven color system approach.

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